EFFECT OF THE MMR SEWAGE PLUME ON THE PRESENT AND POTENTIAL FUTURE HEALTH OF ASHUMET POND

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EFFECT OF THE MMR SEWAGE PLUME ON THE PRESENT AND POTENTIAL FUTURE HEALTH OF ASHUMET POND

INTRODUCTION

This report addresses the health of Ashumet Pond in Falmouth and Mashpee, Massachusetts. Ashumet Pond is threatened by a plume of contaminated ground water that emanates from sand filter beds used for wastewater disposal at the Massachusetts Military Reservation (MMR) approximately 1600 feet upgradient of Ashumet Pond. Since wastewater disposal began at this location in the 1930s, nearly 10 billion gallons of wastewater have been introduced to the ground water upgradient of Ashumet Pond. This report examines the threat to the pond from the phosphorus in the ground-water plume and potential remediation measures to prevent or counteract the effects of the phosphorus plume on the pond. The work reported here was conducted by HydroAnalysis, Inc. under a U.S. EPA Superfund Technical Assistance Grant (TAG) to the Ashumet-Johns Pond TAG Coalition Committee.

Previous studies have identified elevated concentrations of phosphorus and other contaminants in a plume of sewage originating from the MMR wastewater treatment facility (LeBlanc, 1984a; Thurman *et al.*, 1984). Sewage was treated at the plant and the wastewater disposed in 20 sand infiltration beds. The resulting contaminant plume has been mapped as extending from this source over 11,000 feet downgradient in the sand and gravel aquifer. Near the sewage beds the plume has traveled to the south southeast and intersects Ashumet Pond approximately 1,600 feet from the source. From Ashumet Pond, the plume continues in the Ashumet Valley aquifer in a south-southwest direction.

Contaminants in the plume include elevated concentrations of dissolved solids (conductivity), chloride, sodium, boron, detergents, various organic compounds including hazardous substances, various chemical forms of nitrogen, and various forms of phosphorus. The focus of this study is on phosphorus, which has the greatest potential to harm Ashumet Pond.

LAKE EUTROPHICATION

The threat posed by phosphorus is that it is an essential nutrient for the growth of algae and when introduced to a lake in excessive quantities can lead to excessive growth of algae and the condition of diminished water-quality condition known as eutrophication.

The trophic state of a lake is a reflection of the availability of nutrients for the growth of algae. Lakes range from oligotrophic (nutrient poor—literally "poorly fed") to eutrophic (nutrient rich—"well fed"). Ashumet Pond is currently mesotrophic, lying within the middle range between these two extremes. Typically, lakes begin as oligotrophic and, over geologic time, become progressively more and more eutrophic. The speed of this transition depends upon the quantity of organic matter supplied to the lake by its drainage basin and the nutrients recycled within the lake itself.

The process described above, proceeding imperceptibly through geologic time, would hardly seem sufficiently worrisome to provoke concern. However, a lake's natural course can be greatly accelerated by man's activities. Fertilizer from farmlands, wastewater from residential septic systems, and urban rainfall runoff are likely to supply nutrients at a far greater rate than natural processes. The resulting acceleration of the lake's nutrient enrichment hastens the arrival of the eutrophic condition, a process sometimes called cultural eutrophication. In extreme cases, the highly eutrophied condition that results is called a hypereutrophic state. In the instance of Ashumet Pond, there is concern that the influx of phosphorus from the MMR sewage plume will increase the amount of nutrients reaching the pond, leading to cultural eutrophication.

Nutrients and particularly phosphorus play a critical role in lake eutrophication. Although algae require many chemical elements for growth and life processes, the major nutrients are phosphorus, nitrogen, and carbon. On average, plant tissue contains these three elements in the ratio of one part phosphorus (by weight) to seven parts nitrogen to forty parts carbon (Wetzel, 1975). This ratio must be roughly preserved in the plant's nutrient intake as well. According to Liebig's Law of the Minimum, the growth of an organism will be limited by that nutrient which is least relative to the organisms needs. In most lakes this limiting nutrient is the element phosphorus (Wetzel, 1975), and thus studies of lake eutrophication usually focus on phosphorus. In some lakes and at some times of the year, nitrogen or other nutrients may be limiting.

To understand the dynamics of phosphorus in a lake, it is also necessary to understand the lake's thermal structure and hydrodynamics. Most lakes and reservoirs in temperate climate zones show a distinct seasonal cycle in temperature structure with depth. At the end of winter, a lake is typically mixed throughout its depth and shows a vertically isothermal temperature profile—the water is at a constant temperature of approximately 4 degrees Celsius from top to bottom. As the lake surface is warmed by the sun and atmosphere through the spring, the shallowest water warms relative to the deeper

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water. Soon, a distinct layer of warmer and lighter surface water floats atop the cold, heavy deep water. The surface layer is known as the epilimnion; the deep water as the hypolimnion. The intervening layer, in which temperature decreases rapidly with depth, is known as the thermocline. (Technically, the thermocline is defined as the zone in which the change in temperature with depth exceeds 1 degree C per meter.) Through the summer, the thermocline becomes stronger (that is, the change in temperature over the vertical distance of the thermocline increases). Finally, with surface cooling in the fall, the temperature stratification weakens until the fall overturn, when the lake mixes throughout its depth and temperature is once again isothermal.

The period of stratification is very important to lake water quality. The thermocline is a strong barrier to mixing: the configuration of heavy, cold water beneath a layer of much warmer and less dense surface water is highly stable. As a consequence, there is little mixing between the epilimnion and the hypolimnion and the two layers develop distinctly different water quality.

The epilimnion receives sunlight through the water surface and thus supports algae which require sunlight for photosynthesis and growth. Typically in the epilimnion dissolved oxygen is high from atmospheric input and nutrient concentrations low due to algal consumption. In contrast, algal growth is limited in the cooler, darker hypolimnion. Dissolved oxygen must diffuse through the thermocline to reach the hypolimnion and thus is reduced or absent there. Organic matter that settles into the hypolimnion and chemical constituents diffused from the lake bottom increase nutrient and other constituent concentrations, creating a dramatically different water quality than in the epilimnion. In particular, bacterial degradation of organic matter in the hypolimnion may consume oxygen faster than it is replenished and cause the hypolimnion to become anoxic (without dissolved oxygen). In this case, the water chemistry changes so as to enhance the release of the phosphorus from the lake sediments, further increasing the nutrient load to the lake.

The mixing of water from the hypolimnion to the epilimnion may be an important factor in the water quality of the lake. Mixing across a well-established thermocline or within the hypolimnion is very limited. Indeed, lake modeling studies by Wang and Harleman (1982) show that diffusion across and below the thermocline of stratified lakes is at or near the rate of molecular diffusion. Hypolimnetic mixing may be higher if there is significant flow or other motion within the hypolimnion. For example, there may be flow in a reservoir from stream inflows to a deep dam outlet. Another source of motion is an

internal seiche, the back-and-forth oscillation of the thermocline in a type of motion similar to sloshing in a bathtub.

The epilimnion of a lake or reservoir typically is well mixed owing to a nearly constant input of mixing energy from the wind. Occasional strong winds will cause the surface layer to mix into the thermocline and become deeper. This is a far more important mechanism for transport from the hypolimnion to the epilimnion than diffusion across the thermocline.

Other processes that affect the lake's water quality and trophic status are chemical, physical, and biological reactions involving phosphorus. Phosphorus is found in several major forms in a lake, and cycles continuously between those forms. The most basic form for our purposes is the form available for algal uptake, orthophosphate. Orthophosphate is quickly consumed by algae, becoming a part of the particulate phosphorus form. Particulate phosphorus includes phosphorus in living algae as well as in dead algae and inorganic particulates. A portion of the phosphorus in dead algae and inorganic particulates is recycled relatively quickly back to orthophosphate, closing the cycle.

Much of the particulate phosphorus falls to the lake bottom where it joins a large pool of phosphorus in the sediment. Orthophosphate concentrations in the sediment often reach very high levels. Stumm and Stumm-Zollinger (1972) report concentrations in the interstitial water in lake sediments as much as 1000 times greater than typical water column concentrations. Under aerobic conditions, sediment phosphorus is effectively sealed by an oxidized microlayer at the sediment surface. If the water column becomes anaerobic, however, phosphorus in the sediment is released to the water column. For this reason, lake eutrophication may be significantly worsened in lakes in which there develops a strong summer stratification accompanied by oxygen depletion in the hypolimnion.

Studies in 1980 and 1985-86 characterized the trophic status of Ashumet Pond (Duerring and Rojko, 1984; K-V Associates, 1991). Based on a variety of measures, these studies both found the water quality of Ashumet Pond to be generally good, lying within the mesotrophic range. Nonetheless, there was a shift towards greater eutrophication from 1980 to 1985-86 and several indications during the 1985-86 study of impaired water quality. These included anaerobic conditions in the hypolimnion, growth of nuisance algae species, and two documented fish kills.

MMR WASTEWATER TREATMENT PLANT

The wastewater treatment plant on the MMR was first constructed in 1936 to treat 0.9 million gallons per day (mgd) of sewage. The plant was expanded in 1941 to an average capacity of 3 mgd with a peak capacity of 6 mgd. The plant layout, which has changed little since the 1940s, is shown in Figure 1. The treatment system includes primary and secondary wastewater treatment followed by discharge of the treated wastewater to 4 acres of sand infiltration beds. Primary treatment consists of a comminutor which grinds up large solids, an aerated grease-removal unit, and Imhoff tanks which provide for settling and digestion of solids. Secondary treatment consists of biological waste removal in trickling filters followed by settling tanks for additional solids removal. Once treated, the wastewater is discharged into the sand beds.

There are 20 half-acre sand beds for wastewater disposal to ground water. The system was designed to operate 8 beds (4 acres) at any one time, with occasional rotation between beds. The 4 beds closest to Ashumet Pond were operated exclusively from 1977 to 1984 (LeBlanc, 1984b). When operated, the beds are flooded with wastewater which then infiltrates into the soil and percolates to ground water, which is about 20 feet below the bed elevation. LeBlanc (1984a) estimated that a total of 8 billion gallons of wastewater were treated from 1936 to 1980. DEP records show that the plant has operated at much less than full capacity during the 1980s and 1990s, with a permitted flow of 0.8 mgd and an average flow of less than 0.3 mgd. Assuming an average flow of 0.3 mgd brings the total wastewater discharge through to the present to somewhat less than 10 billions gallons.

Beginning in the 1970s, the wastewater treatment plant began to draw attention as the cause of an extensive plume of contaminated ground water. The Town of Falmouth discontinued use of the Ashumet well, a public water supply well located 9,000 feet downgradient of the plant, due to foaming from detergents in the contamination plume. In 1977, the U.S. Geological Survey started a study of the plume and eventually concluded that a plume of contaminated ground water extended more that 11,000 feet downgradient from the disposal beds with a width of about 2,500 to 3,500 feet (LeBlanc, 1984a).

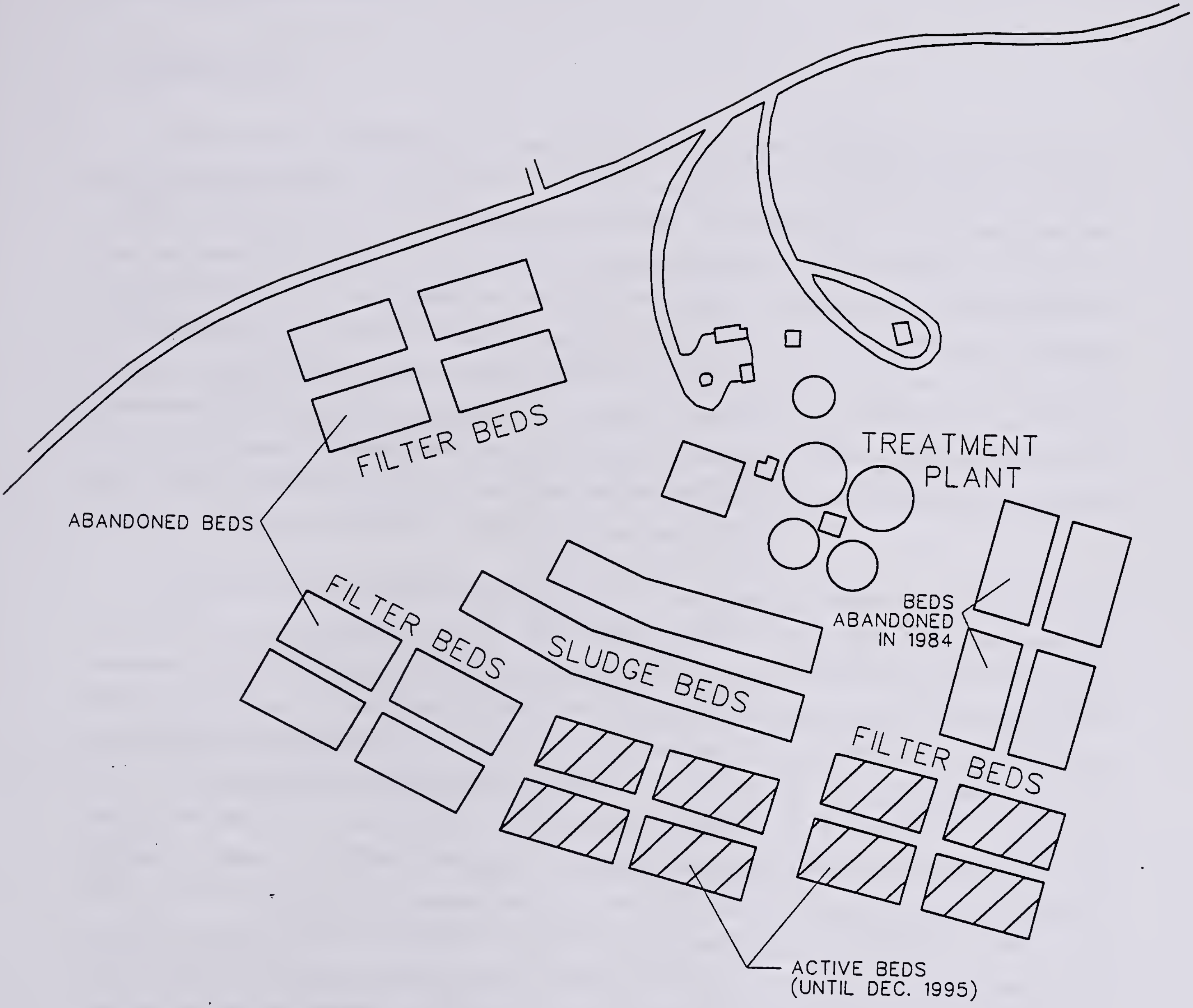


Figure 1

MMR Wastewater Treatment Plant

MMR SEWAGE PLUME

INTRODUCTION

The extent of phosphorus in the MMR sewage plume has been characterized by ground-water samples collected by the U.S. Geological Survey (USGS) in 1978 and 1979 (LeBlanc, 1984a) and 1983 (Thurman *et al.*, 1984). An additional round of samples has been collected since 1983 and is available to the public from USGS data bases, but has not been published in an interpretive report (LeBlanc, 1994). Continuing research studies by the USGS and site characterization studies by the Hazardous Waste Remedial Actions Program (HAZWRAP) have collected additional information on the sewage plume and other aspects of the area hydrogeology. However, none of these studies have reported on the concentrations of phosphorus in the plume and changes in those concentrations over time. Thus, as this study began there had been no published interpretations of phosphorus in the ground water upgradient of Ashumet Pond since 1984.

Figure 2 shows the MMR sewage plume as mapped by LeBlanc (1984a) based on measured concentrations of boron. The plume extends from the MMR wastewater treatment plant initially to the south-southeast where it intercepts Ashumet Pond near Fisherman's Cove. From there, the sewage-contaminated ground water continues to flow in the aquifer beyond the pond, extending over two miles to the south in the Ashumet Valley. Ground-water contamination by chloride and sodium is roughly coextensive with boron; contamination by nitrate and detergents extends even further to the south (LeBlanc, 1984a). In addition, elevated concentrations of chlorinated organic solvents are found in the plume, with concentrations in excess of 100 micrograms per liter (µg/l or parts per billion, ppb) of total chlorinated compounds in several wells (HAZWRAP, 1991). The leading end of the chlorinated solvent plume (delineated by the 5 µg/l contour line) was mapped as having traveled past Hayway Road in 1988 with a predicted rate of advance of about 500 feet per year (HAZWRAP, 1991).

Phosphorus in the ground water has traveled a much shorter distance than other plume constituents (Figure 3). This is because phosphorus is strongly adsorbed to soil particles in the subsurface, a process which impedes travel of the dissolved chemical compared with other chemicals or the flowing ground water. Indeed, it is commonly accepted by environmental engineers that phosphorus effectively does not travel in ground water, and hence is not a constituent of concern for subsurface wastewater disposal.

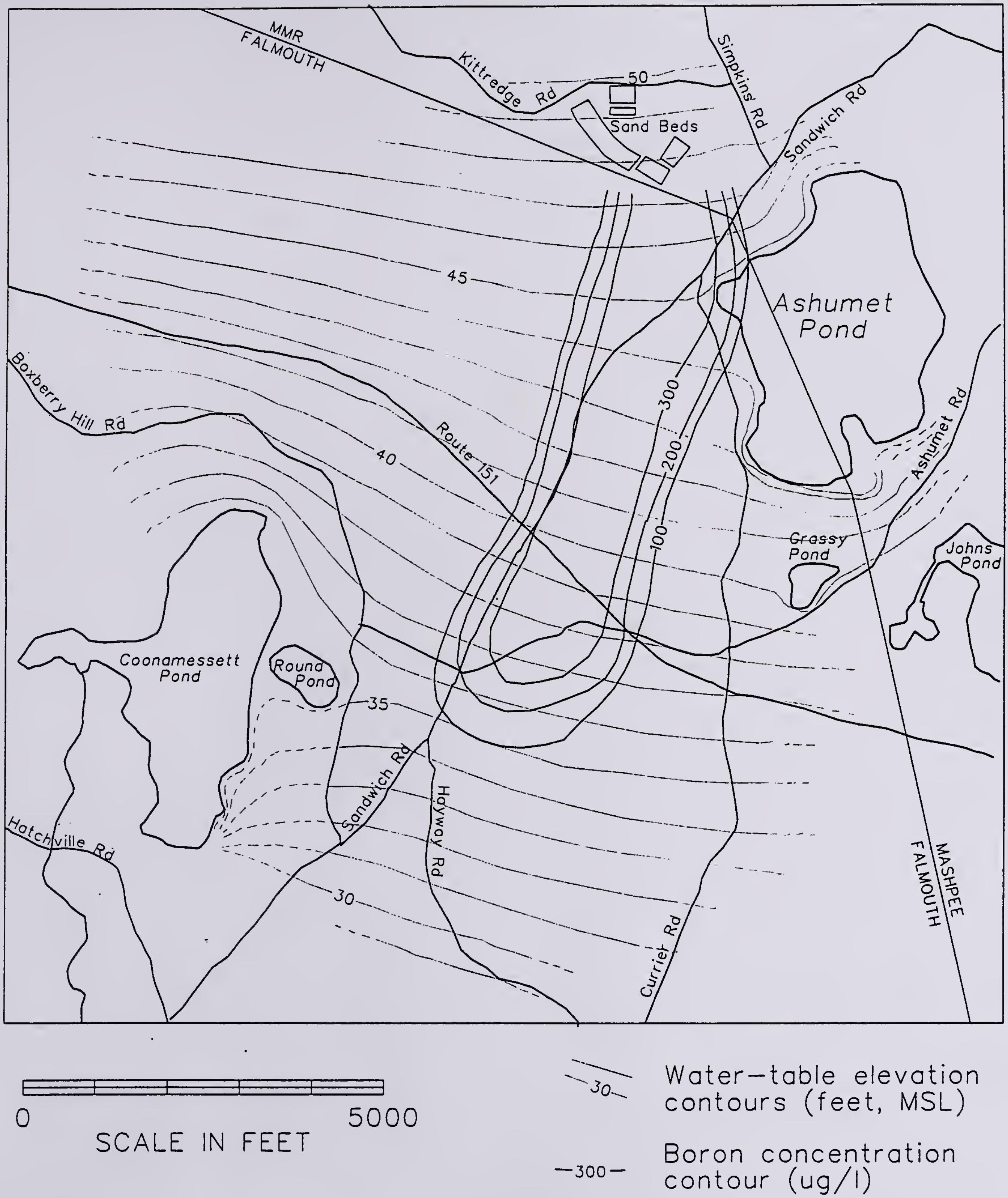


Figure 2

MMR Sewage Plume
Ground-Water Elevation, November 1979 and
Concentration of Boron in Ground Water, 1978-1979
(from LeBlanc, 1984a)

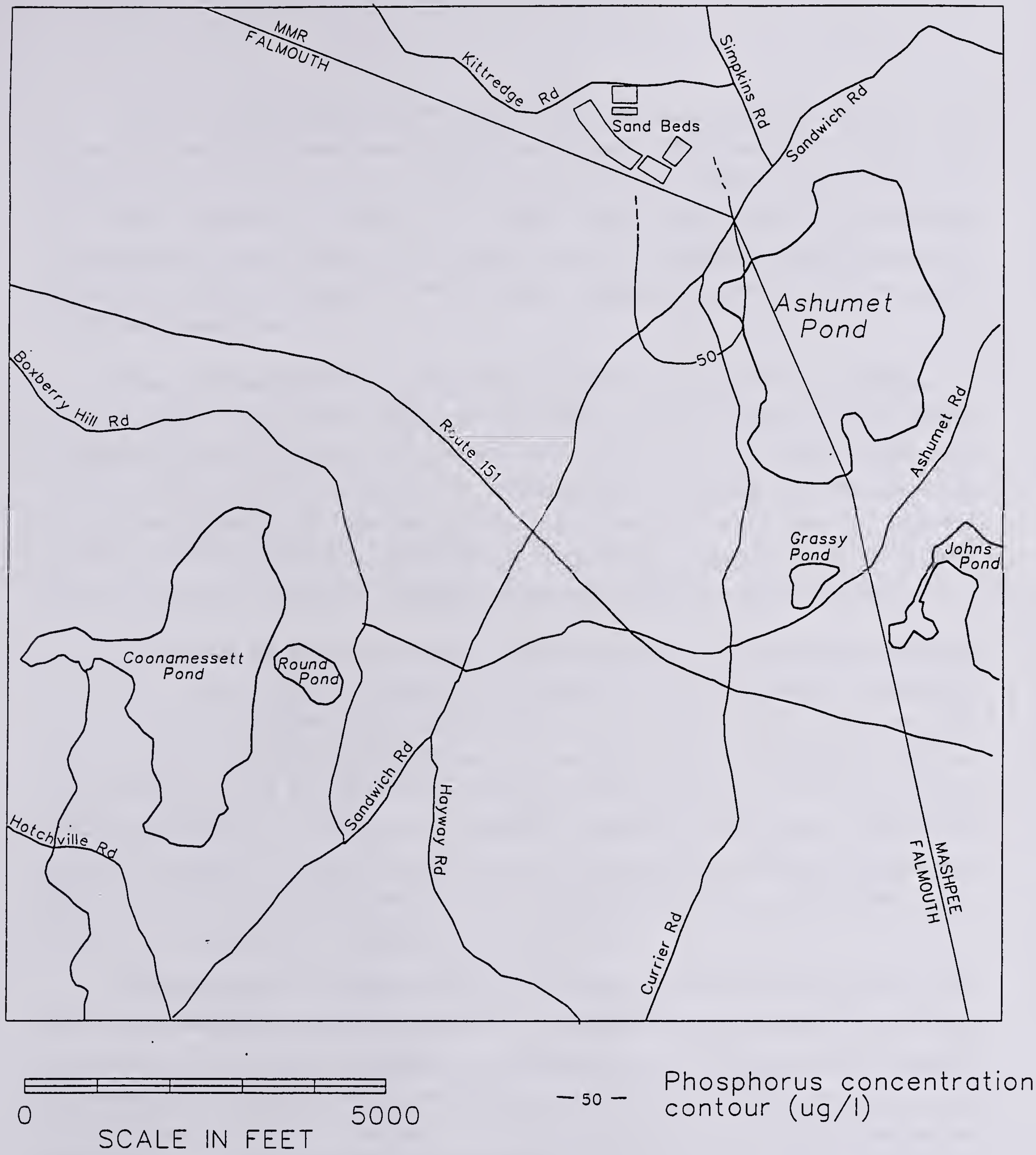


Figure 3

MMR Sewage Plume
Concentration of Phosphorus in Ground Water, 1978-1979
(from LeBlanc, 1984a)

There is an extensive literature showing that adsorption renders phosphorus highly immobile in soil and ground water (Enfield and Bledsoe, 1975; Reneau and Pettry, 1976; Sawhney, 1977; Hill and Sawhney, 1981; Weiskel and Howes, 1992). Isenbeck-Schröter *et al.* (1993), apparently unaware of the MMR plume, state that "no phosphorus contamination of groundwater has been documented yet." Jordan Co. (1988) asserts that phosphorus is immobile in ground water under oxygenated conditions and moves slowly under anoxic conditions.

Phosphorus adsorption in ground water appears to be dominated by adsorption to various metallic oxides, especially ferric hydroxide, and also aluminum and calcium hydroxides (Hem, 1985; Enfield and Bledsoe, 1975; Fox, 1989). Metal oxides typically coat sediment grains in sand and gravel soils (LeBlanc, 1984a), providing plentiful adsorption sites. Once adsorbed, the phosphorus forms nearly insoluble compounds with iron and aluminum. The capacity for adsorption though large is finite. In cases of very high loading the capacity may be reached by exhausting the number of available adsorption sites.

The slowed movement of adsorbing compounds relative to the rate of ground-water movement is often referred to as retardation. Jordan Co. (1988) states that for phosphorus under anaerobic conditions the retardation factor is five, indicating that phosphorus will move five times slower than ground water or conservative salts such as chloride. Even at the MMR site, where phosphorus was discharged into the ground water in apparently sufficient quantities to exhaust the adsorption capacity of the nearby aquifer, the phosphorus plume is at least five times shorter than the plumes of chloride, sodium, and other compounds that do not adsorb. Thus, adsorption did not stop the movement of phosphorus in the Ashumet Valley but greatly slowed it.

LeBlanc (1984a) and Walter *et al.* (1995) document the travel of phosphorus from the wastewater disposal beds to Ashumet Pond. Several studies have shown that sewage-contaminated ground water discharges into Ashumet Pond at Fisherman's Cove. Graphic evidence of the sewage discharge is the growth of algae and a black coating on rocks on the shore immediately north of the cove. The black coating is caused when manganese dissolved in the plume precipitates onto the rocks as the ground water enters the aerated lake water. Analysis of ground-water samples collected where the plume enters Ashumet Pond showed elevated concentrations of phosphorus and other sewage-related chemicals in a comprehensive assessment of the pond by K-V Associates, Inc. and IEP, Inc. (K-V Associates, 1991). Recent studies by Walter *et al.* (1995) discussed below in detail confirm the continued release of phosphorus in the ground-water plume to Ashumet Pond.

RECENT AND CURRENT RESEARCH

The National Guard Bureau has funded recent studies by the U.S. Geological Survey that have recently provided updated information on phosphorus in the MMR plume. Results of studies of the fate and transport of phosphorus in the ground water, aquifer sediments, and ground-water discharge to Ashumet Pond were recently published in a USGS report by Donald A. Walter and others (Walter *et al.* 1995). Mr. Walter is a hydrologist in the USGS Water Resources Division in Marlborough, Massachusetts and is a member of the USGS research group which has studied the sewage plume since the 1970s. The group is headed by Denis R. LeBlanc. Field data collection has continued after the publication of Mr. Walter's report, with recent investigations focusing on the effects of the cessasation in December 1995 of sewage disposal by the MMR sewage treatment plant.

The USGS research project includes both field data collection and analysis. The work in Massachusetts was supplemented by additional laboratory studies conducted in USGS laboratories in Denver and Boulder, Colorado. The field program included collection of ground-water samples from a network of wells and multilevel samplers located between the MMR sand beds and Ashumet Pond. In addition, numerous shallow drive points were temporarily installed and sampled in the shoreline zone of the pond.

Nineteen multilevel samplers at nine sites were utilized. A multilevel sampler consists of a PVC pipe installed in a conventional borehole into the aquifer soils. Each pipe houses numerous small diameter flexible plastic tubes, each of which opens through a small hole (sampling port) to the outside of the pipe and the aquifer. The sampling ports are spaced along the pipe and when sampled provide a detailed vertical profile of contaminant concentrations. Each multilevel sampler was equipped with 15 sampling ports. Up to three multilevel samplers were installed at each site, providing up to 45 vertically spaced samples.

The results of the recent ground-water samples present a very different picture of the phosphorus chemistry in the plume than supposed previously.

The interrelated chemistry of phosphorus and iron suggests that phosphorus mobility is closely related to the iron chemistry of the plume. Biodegradation of the sewage plume has exhausted all dissolved oxygen in the ground water creating anoxic conditions in the downgradient area near the sand beds (Thurman *et al.*, 1984; Walter, 1994b). Farther from the sand beds there is an area of low but nonzero dissolved oxygen. (Walter *et al.*

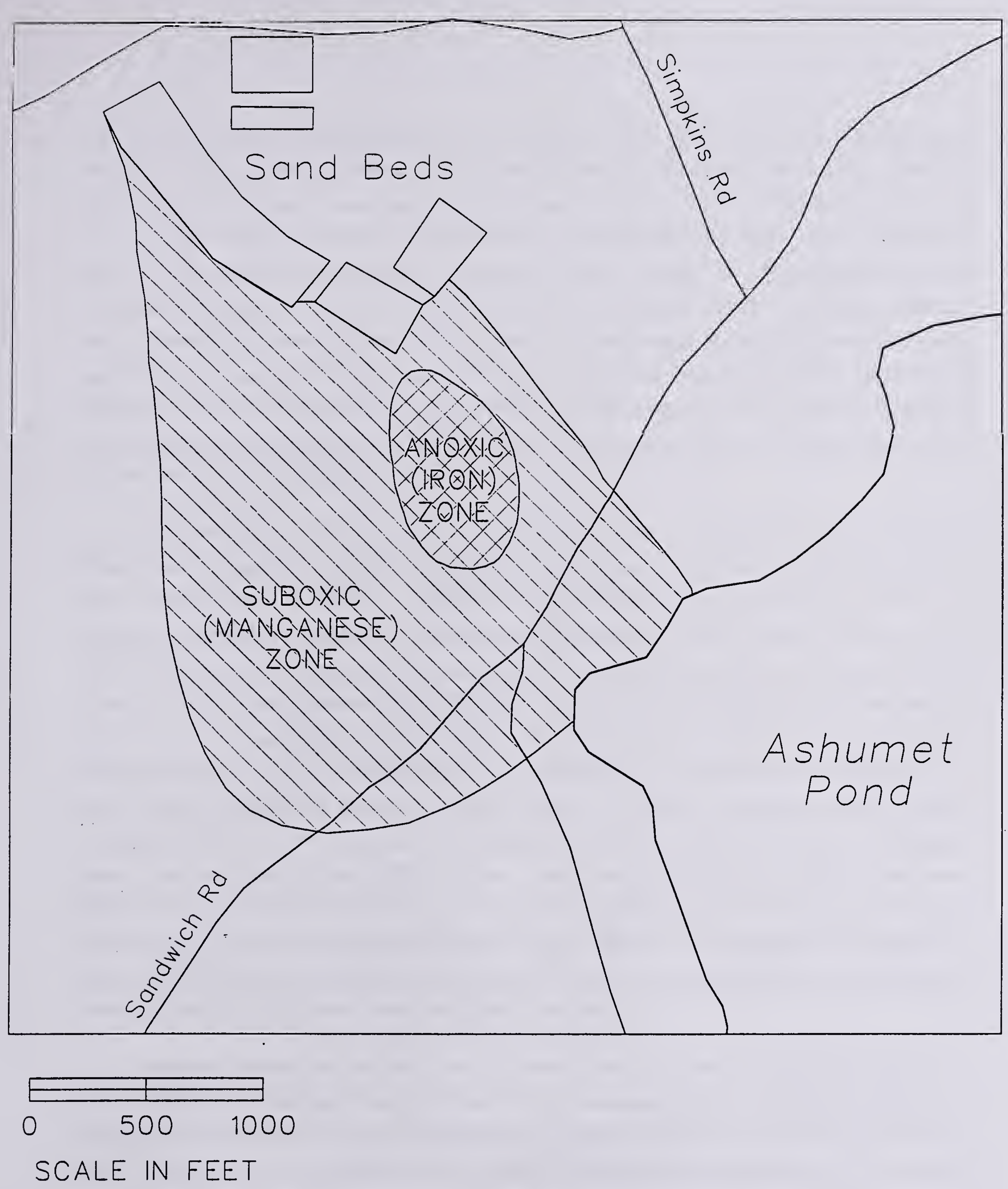


Figure 4

Extent of Anoxic (Dissolved-Iron) and Suboxic (Dissolved-Manganese) Zones Between MMR Sewage Disposal Beds and Ashumet Pond (Walter *et al.*, 1995)

[1995] use a functional definition for such "suboxic" conditions as 0.1 to 1.0 mg/l dissolved oxygen.) Under anoxic conditions, iron is soluble and is therefore being leached from the aquifer solids leading to elevated concentrations of dissolved iron. The anoxic dissolved iron zone (or simply, "iron zone") extends from downgradient the sand beds to about one half to two thirds of the distance to Ashumet Pond (Figure 4). Manganese, which is chemically similar to iron, also becomes soluble under reduced oxygen conditions although less extreme than those for iron. Thus, dissolved manganese is found in both the anoxic and suboxic zones. The suboxic zone occupies an extended area around the iron zone and suboxic ground water reaches and discharges into the pond. The dissolved manganese, upon contact with the aerated water of the pond, precipitates as a black deposit that can be seen on the rocks in Fisherman's Cove.

The mobility of phosphorus is different within and without the iron zone. Phosphorus is generally believed to be more soluble and mobile under anoxic conditions than when oxygen is present. Much of this understanding comes from studies of phosphorus transport across the sediment-water interface in lakes (Wetzel, 1975, pg. 200-227). Phosphorus is recognized as being mobile in the anaerobic layers of buried mud, but immobilized (by adsorption and coprecipitation with iron compounds) when it reaches the aerobic layer of mud at the water surface. Phosphorus in the anoxic iron zone behaves consistently with this model and dissolved phosphorus concentrations are higher in the anoxic zone. In addition, phosphorus forms the low solubility mineral vivianite (ferrous phosphate) under anoxic conditions and there is evidence of phosphorus precipitation within the iron zone of the MMR plume. Gschwend and Reynolds (1987) discovered colloidal-sized particles of vivianite in ground water withdrawn from the iron zone. They hypothesize that the high concentrations of iron together with dissolved phosphate in excess of the adsorption capacity of aquifer solids creates a supersaturation with respect to vivianite, which precipitates in colloidal-sized particles.

Accepted theory would lead one to expect that dissolved or colloidal phosphorus would adsorb and become immobile once it was transported to a suboxic or oxic zone. Walter *et al.* (1995) report that phosphorus has indeed adsorbed to aquifer sediments in these zones, but is nevertheless also present in dissolved concentrations. The reason appears to be that loading of phosphorus from the sewage plume has been sufficient over the years to saturate available adsorption sites and exhaust the capacity to retain phosphorus. Thus, phosphorus is found at elevated concentrations through the anoxic and suboxic zones the full distance to Ashumet Pond (Figure 5).

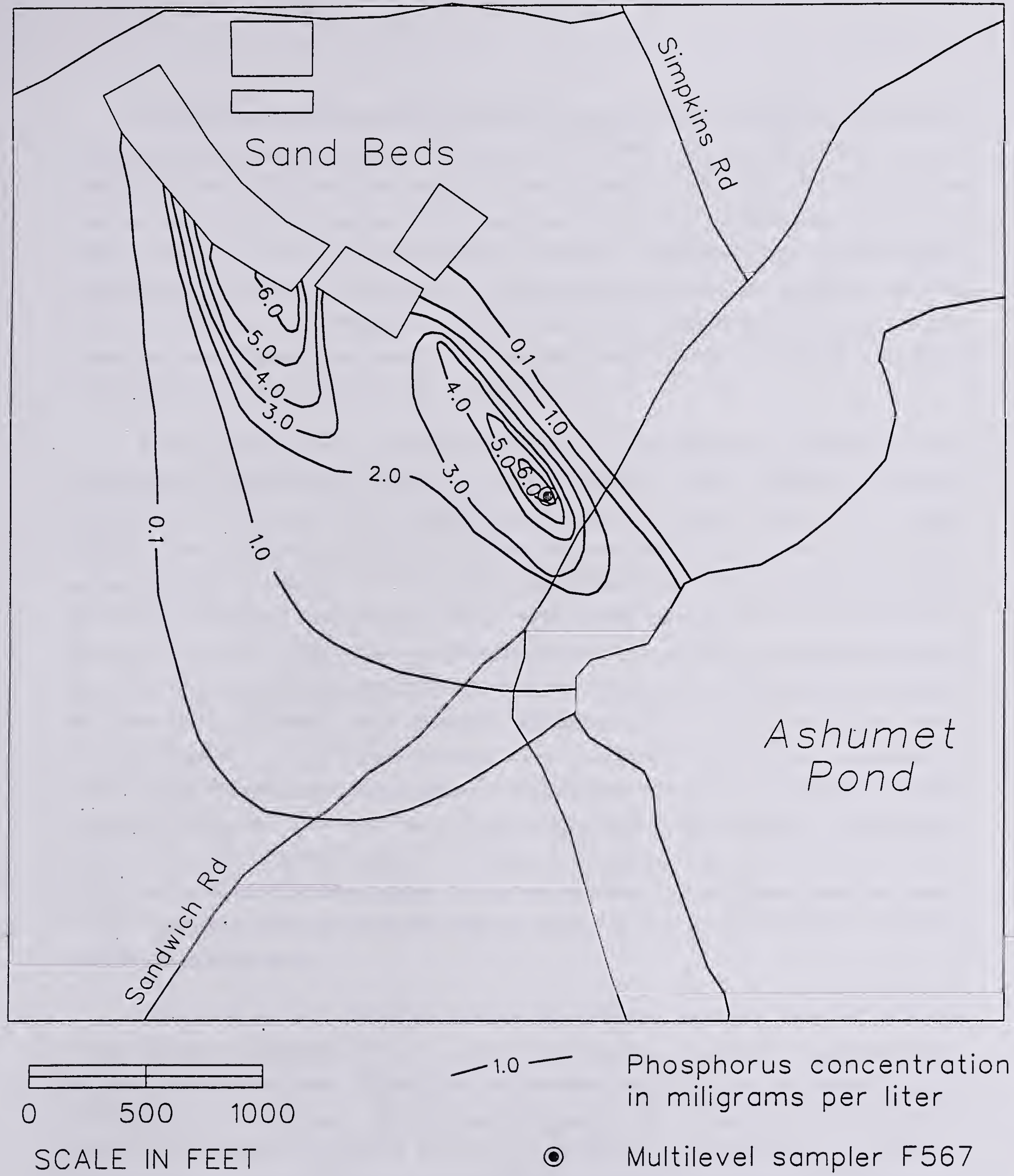


Figure 5

Distribution of Maximum Dissolved-Phosphorus Concentration in Ground Water near Ashumet Pond (Walter *et al.*, 1995)

Some insight into the potential behavior of phosphorus in the aquifer is afforded by laboratory column studies reported in Walter *et al.* (1995). Column experiments involve placing soil in a cylindrical glass column in the laboratory. The ends of the column are then sealed with fittings that include connections to allow water to flow into or out of the column. Water is passed into one end of the column at a measured rate, allowed to pass through the column, and the outflowing (effluent) water collected at the other end. The amount of water passed through the soil is typically measured in terms of pore volumes where one pore volume is the amount of water that would fill all of the empty pore space between the particle grains of the soil in the column.

Walter (1994) estimates that 95 to 99 percent of the phosphorus discharged from the treatment plant remains adsorbed to aquifer sediments. Thus, considerable attention was devoted in his study to the phosphorus absorbed to aquifer solids. Soil samples collected from within the phosphorus plume show considerable quantities of phosphorus associated with the solid phase. Soil cores were collected from within the different zones of the plume and flushed with uncontaminated water in laboratory columns. Soil cores from the anoxic (iron) zone rapidly released phosphorus and the phosphorus concentration in the column effluent reached zero within about four pore volumes of flushing. Soil cores from the suboxic (manganese) zone released phosphorus at a slow rate (and lower concentrations) for over 100 pore volumes, never reaching a zero effluent concentration despite a significantly lower initial effluent concentration than from the anoxic cores. This slow phosphorus was, however, preceded by a sharp “spike” in the effluent concentration that lasted about 11 pore volumes. A similar spiking phenomenon was found in other column experiments discussed below. It was not observed in the effluent from the anoxic sediment columns, although the entire effluent history of those columns could be viewed as a single phosphorus spike.

Differences in iron chemistry explain the different behavior observed with the anoxic and suboxic columns. The iron in the anoxic sample precipitates when contacted by the clean, oxygenated water. Phosphorus coprecipitates with the iron or adsorbs to newly precipitated iron compounds. As well, the iron may create an insoluble iron precipitate coating on the sediment grains as well as on any phosphorus adsorbed to the sediment. Such a coating could effectively seal the phosphorus, making it unavailable for desorption. The soil core from the suboxic zone on the other hand has no free iron to precipitate; thus precipitates, coprecipitates, and coatings are not formed and phosphorus continues to desorb.

Walter *et al.* (1995) also collected clean soil cores from outside the plume and used these in other column experiments. In these experiments, a clean soil core was subjected to sewage-contaminated ground water withdrawn from the suboxic zone. Phosphorus, which was present in the influent at a concentration of 0.49 mg/l, began to elute from the column after about 50 pore volumes, indicating the apparent exhaustion of adsorption sites on the sediment. After 100 pore volumes, the phosphorus concentration of the column effluent reached a plateau at a concentration near that of the column influent. At this point, the water passed into the column was changed to uncontaminated water. The phosphorus concentration in the effluent suddenly "spiked" to much higher concentrations, and then decreased. The spike lasted about 10 pore volumes, after which concentration decreased fairly rapidly and steadily. The observed phosphorus concentration spike was not expected and is not completely understood. Walter *et al.* (1995) attribute the phosphorus spike to the fact that some of the phosphorus is loosely sorbed to sediment and thus readily released when the uncontaminated water passes through. This is consistent with the conceptual model presented by Isenbeck-Schröter *et al.* (1993). They hypothesize a two-step adsorption process in which phosphorus is first adsorbed to the solid surface by ion exchange and then slowly forms a solid solution with the iron hydroxides. The first step is quick and reversible; the second is slow but forms poorly soluble oxides and hydroxides.

Phosphorus concentrations are generally lower outside the iron zone than within although there are exceptions. Particularly, multilevel sampler F567, newly installed for the phosphorus investigation, showed the highest observed concentrations of phosphorus anywhere in the ground-water plume. Significantly, F567 is located outside the iron zone approximately 1000 feet upgradient of Ashumet Pond, east of the core of the plume (Figure 5). It is directly downgradient of the northeast-most sand beds at the MMR treatment facility. These beds were the only beds used from 1977 to 1984, when the discharge was shifted to beds further from Ashumet Pond (LeBlanc, 1984b). (Computer modeling by LeBlanc (1984b) predicted that the shift of the sewage loading to the west would reduce the phosphorus load to the pond.) The high phosphorus zone thus appears to be immediately downgradient of a longtime source of phosphorus-containing sewage that was ended in 1984. The highest observed concentration at F567 is greater than 6 mg/l, several times greater than the previously detected high concentration. Walter *et al.* (1995) report that specific conductance values at F567 suggest that the high phosphorus concentrations occur where uncontaminated and contaminated ground water are mixing.

The lack of historical data for this newly found high phosphorus zone raise several questions. It is unknown how long this elevated phosphorus zone has existed, whether it originated from the influx of clean water following retirement of the upgradient sand beds, and whether it is moving over time. However, Walter *et al.* describe a troubling possibility based on the analogy with their column study experiments: that the elevated phosphorus observed at F567 is essentially the same thing as the phosphorus spike observed in the column effluent. This is troubling because it implies that there is ground water with much higher concentrations of phosphorus than previously observed traveling towards Ashumet Pond at an uncertain rate. Alternatively, they indicate the elevated phosphorus concentration may simply represent a zone of higher phosphorus concentrations associated with the particular beds that are upgradient. The phosphorus at this location needs to travel an additional 1000 feet before it reaches the pond.

It is useful to consider the time frames of phosphorus migration from the MMR wastewater treatment plant to Ashumet Pond. The ground-water velocity downgradient from the MMR is about 1.6 feet per day (Walter *et al.*, 1995). As stated above, phosphorus travels more slowly than ground water owing to adsorption on aquifer solids, a process known as retardation. Comparison of the phosphorus plume (Figure 3) with the unretarded boron plume (Figure 2) suggest that the retardation factor for phosphorus may be as little as about 5. The resulting rate of phosphorus travel is about 0.3 feet per day. At this rate, it would take about 15 years for phosphorus to travel the 1600 feet from the nearest sewage beds to Ashumet Pond and about 10 years from the area of highest phosphorus concentrations. This appears to be somewhat consistent with the observed extent of the phosphorus plume. For example, if we assume that the high concentrations of phosphorus correspond to a retarded front of clean water advancing from the MMR since use of the easternmost beds ceased in 1984, the rate of travel is about 600 feet in 9 years and the retardation factor is about 9. At this rate, the front of elevated phosphorus would reach the pond in about 29 years.

Related to the question of travel time is the time to flush the reservoir of accumulated phosphorus adsorbed to the aquifer sediments. The USGS column studies showed that more than 160 pore volumes were required to flush phosphorus from the soil core once clean water was introduced. This would correspond to hundreds of years to flush phosphorus from the zone between the MMR disposal beds and Ashumet Pond.

Other data collected by Walter *et al.* (1995) characterized the nature of the ground water discharging to Ashumet Pond. Shallow well-point samplers were temporarily

installed along about 1500 feet of shore. The concentration of phosphorus in the ground water is elevated above 0.01 mg/l along about 700 feet of shore, with a peak concentration at one sampler of 1.9 mg/l. Measurements in 1985-86 by K-V Associates (1991) found total phosphorus concentrations between 0.035 and 0.20 mg/l at four locations where the plume enters the pond. The higher concentrations measured recently imply a higher load of phosphorus to the pond than previously calculated. Walter *et al.* computed the load of phosphorus discharged from the sewage plume into Ashumet Pond as varying between 130 and 167 pounds of phosphorus per year with an average of about 150 pounds per year. These compare with earlier estimates of 82 pounds/year by K-V Associates (1991) and 41 to 125 pounds/year by Jordan Co. (1988). A severalfold increase above any of these estimates can be anticipated if the newly identified zone of elevated phosphorus migrates to the pond.

Several questions pertinent to the effects of ground-water on the pond remain although they may be addressed by additional studies by the USGS or Guard Bureau. Obvious questions concern the recently observed zone of elevated phosphorus. The chemistry of phosphorus in this zone is uncertain as is its mobility and rate of movement. The potential for high concentrations of phosphorus to reach the pond is also uncertain. The elevated concentrations are relatively deep in the aquifer and could conceivably flow under and never discharge to the pond.

More fundamental questions concern the chemistry of phosphorus in the different zones in the ground water. These are critical insofar as the development of *in-situ* remedial measures to remove or immobilize phosphorus in the ground water depends upon understanding the chemistry. For example, *in-situ* aeration (air sparging) has been suggested as a possible remedial measure. However, the column experiments by the USGS which showed a phosphorus spike when clean water was washed through a contaminated column suggest that aeration could simply liberate more phosphorus, the exact opposite of what is intended. Presently, there is not a sufficiently complete conceptual model of the phosphorus system in the ground water to predict remedial system performance with confidence.

WATER QUALITY OF ASHUMET POND

MEASURED TRENDS

As this study commenced, the situation with respect to data characterizing Ashumet Pond was essentially similar to that for ground water. The most recent prior study was a comprehensive evaluation by K-V Associates (1991) with data collection in 1985 and 1986. No data on the lake itself had been collected and published subsequently.

The absence of recent lake water-quality data presented a problem inasmuch as both K-V Associates (1991) and Jordan Co. (1988) predicted increased eutrophication over time as the result of continually increasing phosphorus loads. Without new data, the validity of these predictions could not be evaluated. Fortunately, this situation has been corrected with the Ashumet and Johns Ponds Study now being conducted by HAZWRAP (1992).

The Ashumet and Johns Pond Study was planned to address residents' concerns regarding the potential effect of the MMR on Ashumet and Johns Ponds. It includes tasks to collect data to characterize ground- and surface-water quality, sediment quality, stormwater quality, benthic algae, and fish. It provides for quarterly and annual reports on the study progress. This report is based upon quarterly reports for both 1993 and 1994 (HAZWRAP, 1993a, 1993b, 1993c, 1994, 1995a, 1995b, 1995c) and annual reports for 1993 and 1994 (HAZWRAP, 1995d, 1995e). The quarterly reports include numerous tables of collected data whereas the annual reports provide data summaries and narrative.

In an earlier interim report, we noted several deficiencies in data collection and reporting in the Ashumet and Johns Ponds Study reports. These included a failure to report several common measures of lake trophic status including chlorophyll-a, lake transparency (Secchi disk depth), and total phosphorus. Further inquiry with HAZWRAP revealed that chlorophyll-a and lake transparency data had in fact been measured but were just not reported. Chlorophyll-a and lake transparency data collected during the entire HAZWRAP program through June 1994 are included in Quarterly Report 2 for Year 2 (HAZWRAP, 1994c). Total phosphorus was not being collected, although that omission was corrected with the December 1993 samples for Ashumet Pond. A summary of selected data pertinent to the trophic state of Ashumet Pond is included as Appendix A.

The available data allow a qualitative evaluation of the changes in Ashumet Pond from 1980 to 1985-86 and 1992-94. Figure 6 shows the location of sampling points in

Ashumet Pond; Figures 7 and 8 show the results of the available measurements. Many of the data from the K-V Associates study (1991) were available only in plotted graphs rather than as numerical values in tables. Accordingly, the 1985-86 values shown in Appendix A and plotted in Figures 7 and 8 were for the most part determined by scaling values off of figures in the K-V Associates report.

Figure 7 shows values of three traditional measures of lake eutrophication, the concentration of chlorophyll-a, transparency, and total phosphorus. These parameters form the basis for the commonly used trophic state index (TSI) by Carlson (1977). The 1992-94 concentrations of chlorophyll-a are generally double those in 1985-86 or more. K-V Associates (1991) show between 1 and 3 μg/l chlorophyll-a through much of the year, with a June peak of 4 to 5 μg/l and a winter peak of 8 μg/l. In the highest readings, the HAZWRAP (1994) data show between 20 and 37 μg/l in September 1994. Chlorophyll-a is nearly a direct measure of lake eutrophication in that it basically measures algal concentration. High concentrations of algae produce the undesirable symptoms most often associated with eutrophication such as turbid water, unpleasant taste and odor, and floating scums or mats of algae. The TSI for the average chlorophyll-a concentration in 1992-1994 places Ashumet Pond on the borderline between mesotrophic and eutrophic whereas readings in 1985-86 were at the oligotrophic-mesotrophic border.

Measurements of lake transparency and total phosphorus (Figure 7) show less change than chlorophyll-a from the earlier measurements in 1980 and 1985-86. The total phosphorus data show generally comparable or lower concentrations in 1992-94 than in 1985-86. Transparency has increased slightly. Both the higher transparency and occasionally lower phosphorus are contrary to the increased concentrations of chlorophyll-a. The apparent anomaly in the transparency readings is analyzed in Figure 9, which compares the field measured values of transparency and chlorophyll-a with Carlson's empirical correlation between those parameters. This comparison shows that the HAZWRAP Secchi-disk readings are higher than expected for the upper range of chlorophyll-a readings. Possible explanations for the discrepancy may be a change in phytoplankton speciation that results in clearer water, field error, or erroneous chlorophyll-a measurements. The last seems the most likely.

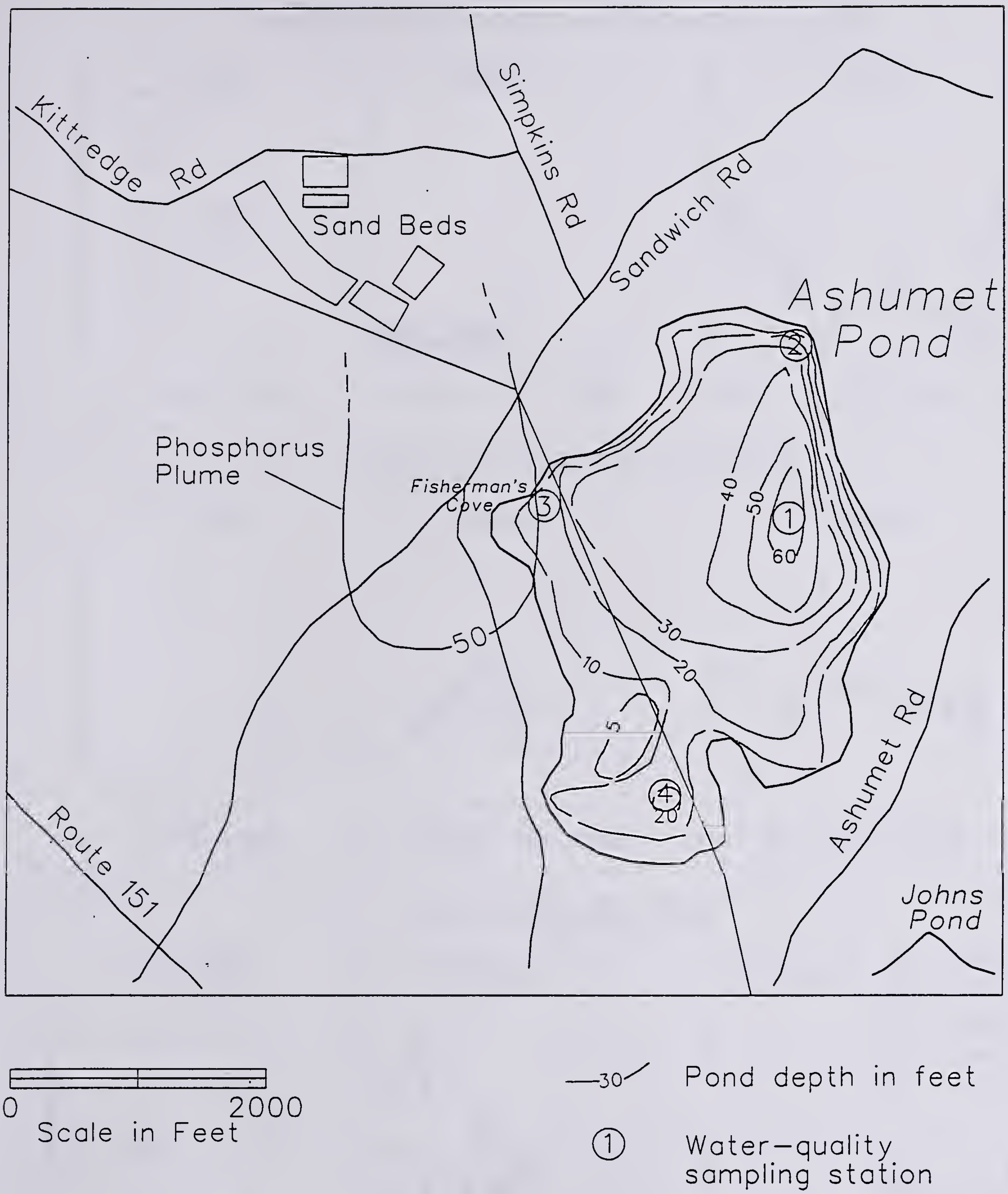


Figure 6

Sampling Locations in Ashumet Pond

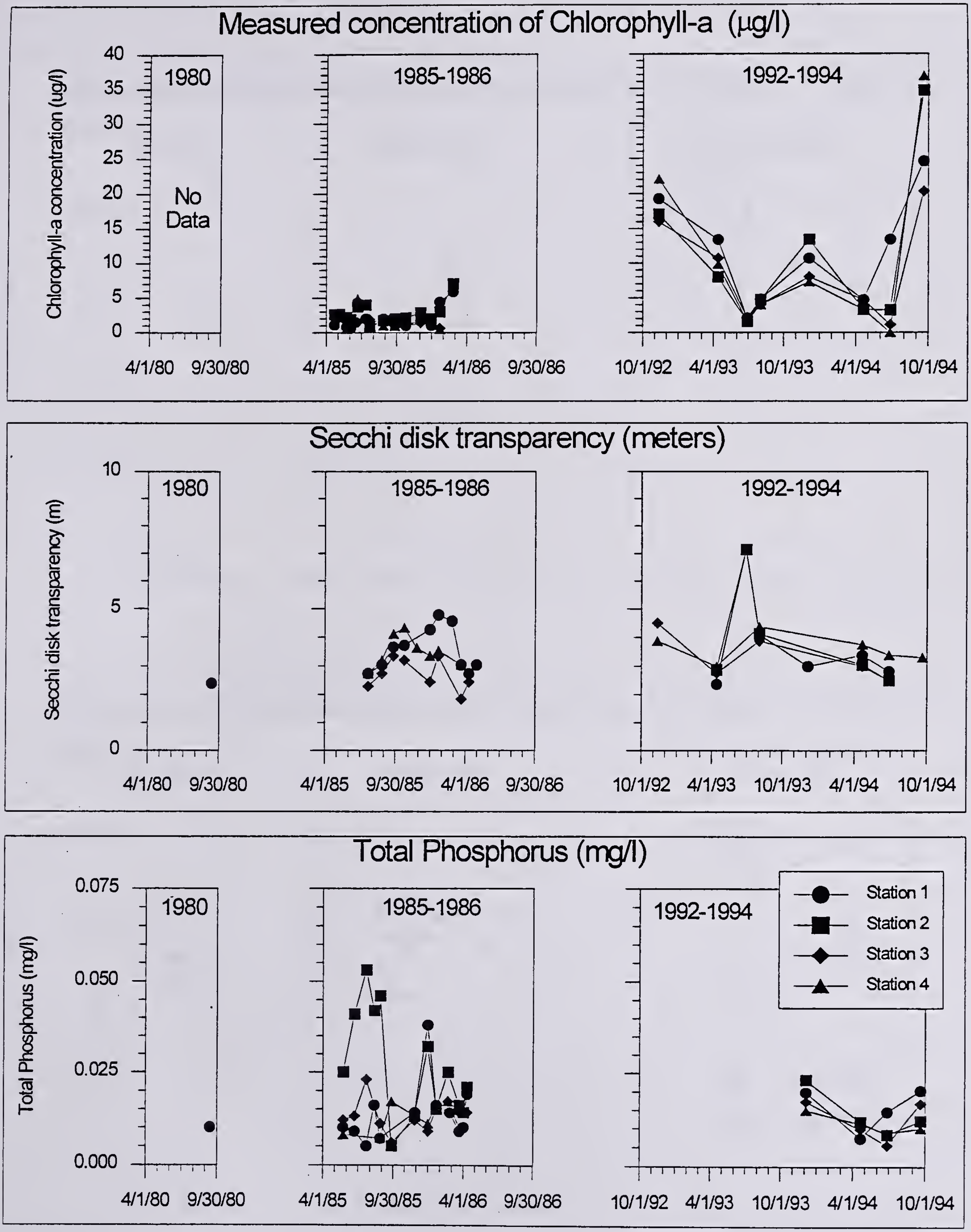
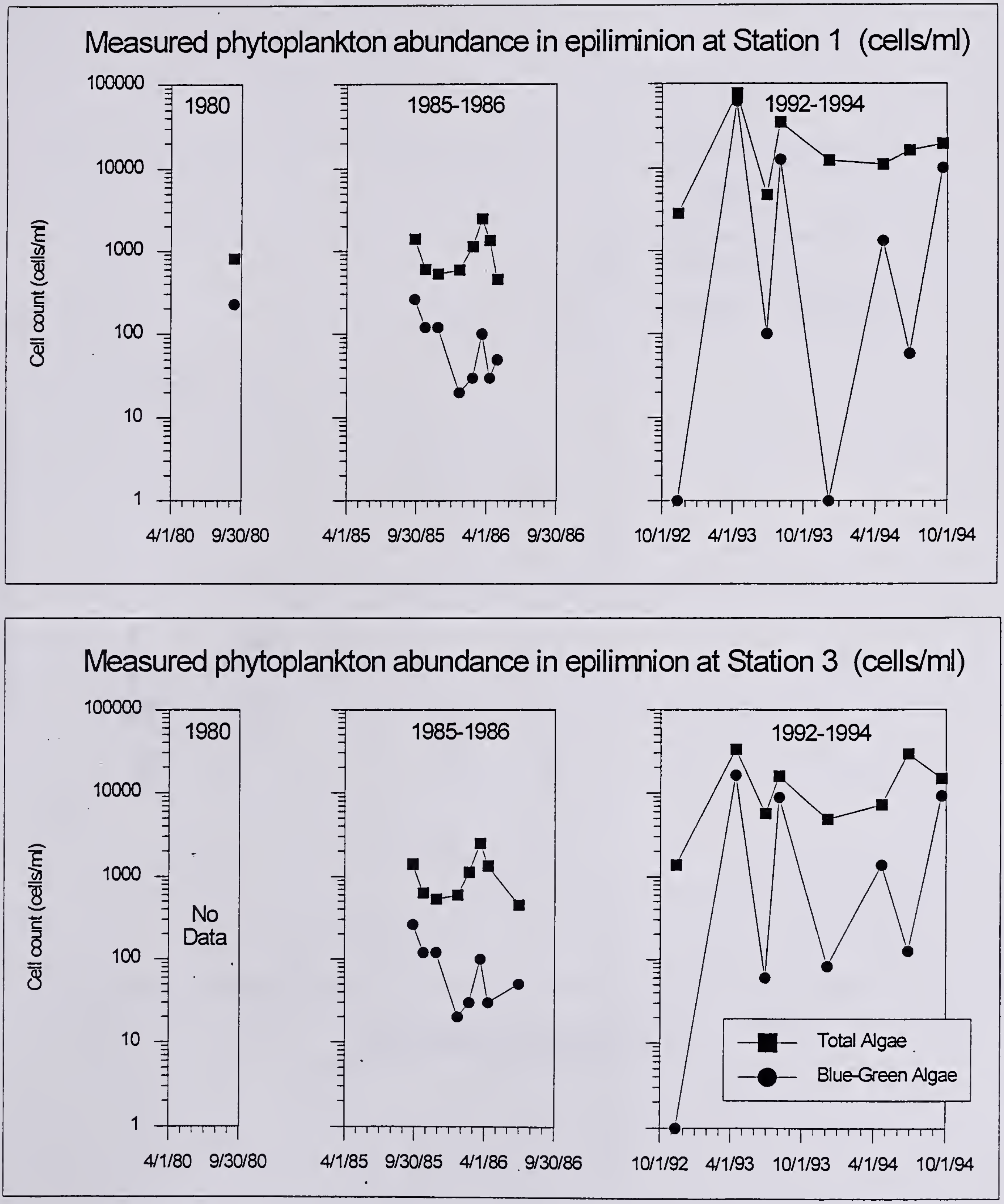


Figure 7

Measured Trophic State Indicator Parameters in Ashumet Pond


Measured phytoplankton abundance in epiliminion at Station 1 (cells/ml)

Measured phytoplankton abundance in epilimnion at Station 3 (cells/ml)

Figure 8

Measured Phytoplankton Abundance in Ashumet Pond

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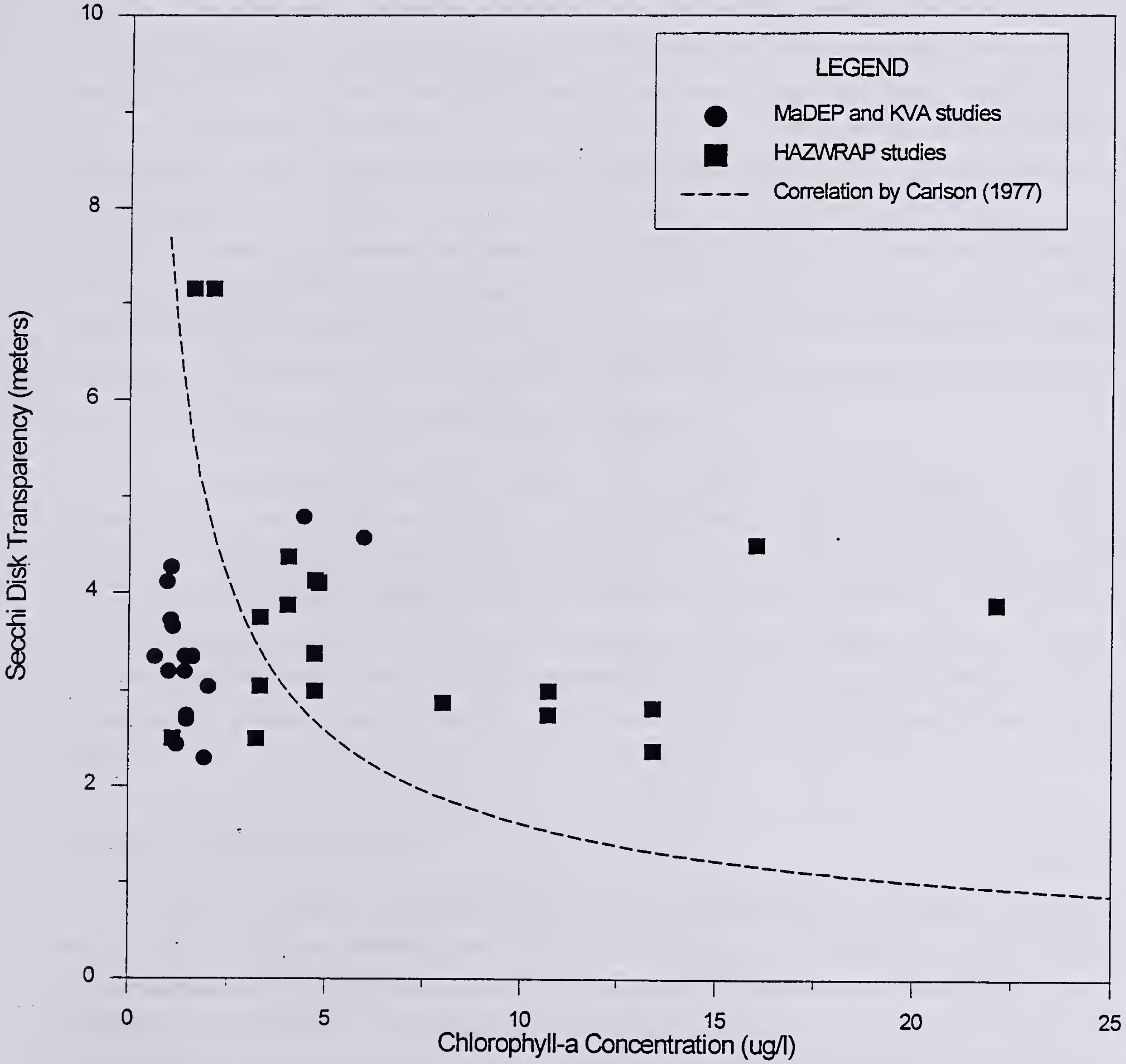

Figure 9

Comparison of Measured Secchi Disk Transparency and Chlorophyll-a Values

Phytoplankton (algae) abundance offers another very direct measure of trophic status although counting techniques can be variable and biomass may be a more reliable measure. Biomass measurements are not available for other than the 1992-94 period, however. Measurements are shown in Figure 8—note that the vertical axis is logarithmic and thus the highest concentrations shown for 1992-94 are 10 to 100 times greater than those for 1980 and 1985-86. Peak phytoplankton cell counts have increased substantially. Peak counts reported by K-V Associates (1991) for Station 1 are approximately 2,500 cells per milliliter (cell/ml) whereas HAZWRAP (1993, 1994) shows a peak concentration of 77,208 cell/ml in April 1993. The K-V phytoplankton distribution shows diatoms to be dominant in terms of number whereas the HAZWRAP data show blue-green algae to dominate in April. The blue-green algae are a much less desirable species of algae and are associated with eutrophication, impaired taste and odor, and other water-quality problems. A caveat is that comparisons between species based on species abundance (cell count) may be less conclusive that a comparison based on biomass.

The increase in phytoplankton abundance is consistent with the changes seen in the chlorophyll-a concentration in Figure 7 and inconsistent with the transparency and phosphorus measurements. Of these, transparency is the simplest measurement and probably the least prone to error. Thus, the available data do not indicate a clear trend in the water quality and trophic state of the lake over time between 1980 and 1994. Continued measurement of at least the trophic-state indicator parameters is recommended to continue to evaluate trends over time and identify any adverse changes in lake water quality.

EUTROPHICATION ANALYSIS

There are a variety of methods to evaluate lake eutrophication. Originally, the plan for this study called for assessing the condition of Ashumet Pond using a numerical lake eutrophication model. However, as the study progressed it became clear that such a model would have limited utility. The available field data make clear the nature and causes of the pond's problems, and little additional information is likely to be gained by complicated numerical simulation. Instead, we have adopted a more simple and practical approach by using a widely used and accepted analytical model developed by Richard Vollenweider based on a phosphorus loading concept.

The Vollenweider equation gives the steady-state concentration of phosphorus in lake water as (Reckhow and Chapra, 1983):

$$P = \frac{L}{Z} \frac{1}{\frac{1}{\tau} + \sqrt{\frac{1}{\tau}}}$$

where, P is the steady-state concentration of phosphorus in the lake (M/L^3);

L is the phosphorus loading rate per unit surface area of the lake ($M/T/L^2$);

Z is the average depth of the lake (L); and

τ is the hydraulic residence time of the lake (T).

Although the Vollenweider model simplifies the pond's dynamics considerably, it is built upon a solid base of empirical data and has proven to be a highly useful predictor of lake eutrophication (see for example van Straten, 1986).

Values of the parameters used in the Vollenweider model for Ashumet Pond are available from previous studies. The mean depth of Ashumet Pond is 23 feet (7 meters) and the surface area is 203 acres (82 hectare) (K-V Associates, 1991). The hydraulic residence time is estimated to be 1.71 years by Jordan Co. (1988) and 1.89 years by K-V Associates. This report uses the average of these values, 1.8 years. The estimated phosphorus load varies in the previous studies and all estimates are used here (see Table 1). The total load listed for the USGS in Table 1 adds their estimate of the MMR plume load to the K-V estimate for all other loads.

Table 1 uses the Vollenweider model and the phosphorus loading data to predict the concentration of total phosphorus in Ashumet Pond. The trophic state is also shown, based on the following approximate delineation by Vollenweider (NALMS, 1990):

Trophic State	Total Phosphorus Concentration
Oligotrophic	< 10 µg/l
Mesotrophic	10 - 25 µg/l
Eutrophic	25 - 60 µg/l
Hypereutrophic	> 60 µg/l

Table 1

Predicted Phosphorus Concentration in Ashumet Pond using Vollenweider Model

	Phosphorus Load from MMR Plume (kg/yr)	Total Phosphorus Load (kg/yr)	Percentage Load from MMR Plume (%)	Areal Phosphorus Loading Rate (g P/m^2-yr)	Predicted Phosphorus Concentration (µg/l)	Corresponding Trophic State
K-V Associates, 1991	37	126	30	0.15	17	Mesotrophic
Jordan Co., 1988						
Present, best case	19	70	27	0.09	9	Oligotrophic
Present, worst case	57	145	39	0.18	19	Mesotrophic
Future, best case	187	241	78	0.29	32	Eutrophic
Future, worst case	375	466	81	0.57	62	Hypereutrophic
Walter *et al.*, 1995	67	155	44	0.19	21	Mesotrophic
Future elevated phosphorus zone migration scenario	205	293	70	0.36	39	Eutrophic
No MMR-plume scenarios						
Best case	0	51	0	0.06	7	Oligotrophic
Worst case	0	88	0	0.11	12	Mesotrophic

The predicted phosphorus concentrations in Table 1 compare reasonably with those actually observed. The estimate of 17 µg/l based on the loading estimate by K-V Associates (1991) agrees exactly with the average measured total phosphorus concentration at the four epilimnion stations during 1985 and 1986. The range during the 1985-86 period was between <5 to 53 µg/l, wider than the predictions based on the Jordan Co. range of estimates for the present load. The prediction of 21 µg/l based on the USGS estimate of the load is somewhat higher than the averages of total phosphorus during the 1992-94 program which varied between 12 and 17 µg/l at the four epilimnion stations.

A future scenario assuming migration of the high phosphorus concentrations observed recently is also considered in Table 1. The detailed water-quality data to estimate a loading rate are unavailable, but the peak phosphorus concentration at cluster F567 is about three times higher than the peak now at the pond's edge. Therefore, the

estimated load from the MMR plume is tripled under this scenario and added to the K-V estimate for all other loads. The estimates of possible future scenarios made previously by Jordan Co. (1988) bracket the estimate for the elevated phosphorus migration scenario. Thus, the phosphorus migration scenario was effectively (although not specifically) anticipated in the prior work. In this sense, the new USGS findings do not worsen the outlook for the pond although they certainly add gravity to previous predictions by identifying specific conditions in the ground water consistent with possible increased future loads.

The predicted concentrations of phosphorus clearly indicate an adverse situation for Ashumet Pond. The recent loading estimate by the USGS approaches the eutrophic range and all future estimates are well into the eutrophic range. Field measurements confirm that total phosphorus is already occasionally within the eutrophic range.

The degree to which the MMR plume contributes to the degradation of Ashumet Pond is shown in the last scenario in Table 1. This scenario takes the Jordan Co. loading estimates, subtracts out the MMR plume contribution, and determines the total phosphorus concentration and trophic state in the absence of the MMR plume. (The difference in loading between the present and future scenarios by the Jordan Co. is almost entirely due to changes in the MMR plume load, thus the remaining load is essentially the same for the present and future scenarios.) This comparison makes clear that the threat to the water quality of Ashumet Pond comes from the MMR plume. Absent that source, the pond would have a trophic state near the oligotrophic-mesotrophic boundary. Future predictions of eutrophic or hypereutrophic conditions derive entirely from the MMR plume loading.

Overall, the recently collected ground-water and lake data show that the water quality of Ashumet Pond is seriously threatened. Based on recent USGS measurements and loading estimates, the MMR plume roughly doubles the total phosphorus load to the pond and thereby alters the trophic state of the pond. Possible future increases in the phosphorus discharged to the pond by the MMR plume are predicted to cause the pond to transition to a eutrophic or even a hypereutrophic condition.

POTENTIAL REMEDIAL ALTERNATIVES

The likelihood of future increases in phosphorus loads to Ashumet Pond from the MMR plume creates both a threat and an opportunity. Although there are today clear adverse effects on Ashumet Pond, they are not yet at a critical stage. Future conditions may be very much worse, with significant changes in the condition of the pond as phosphorus from the plume enters the pond at increasing rates. There is an extensive literature and experience base for restoration of eutrophied lakes (for example, Cooke *et al.*, 1993). However, the results of such restoration efforts are often temporary and only partially successful. A far more desirable strategy for Ashumet Pond is to remedy the phosphorus plume in the ground water before the core of the plume reaches the pond.

Unlike the data base for lake restoration, there is essentially no guidance from the technical literature or past experience on remediation of a phosphorus plume in ground water. As discussed above, the accepted paradigm is that phosphorus does not migrate in ground water but is instead adsorbed to aquifer solids. A thorough search of the literature found only a few examples of phosphorus transport in ground water and no guidance on remediating a phosphorus plume. Nonetheless, previous studies of the MMR plume have offered a number of ideas for in-ground remediation alternatives. These and other alternatives are described below.

Extraction of phosphorus-contaminated ground water by pumping followed by treatment and disposal. This alternative was suggested and assessed in some detail by K-V Associates (1989). "Pump-and-treat" is a straightforward technology and is the most frequently implemented ground-water remedy at hazardous waste sites. The concept is that one or more ground-water extraction wells are located downgradient of a contaminant source and pumped at such a rate as to capture the flowing contaminated ground water. In some installations, wells are installed only at the downgradient end of the plume to prevent continued contaminant migration. In other installations, wells are located at several points along the axis of the plume in order to speed the cleanup process.

At Ashumet Pond, there is a complication with the pump-and-treat technology in that it would divert ground water that would otherwise travel to Ashumet Pond and could induce outflow from the pond to the pumping wells. K-V Associates (1989) present a system consisting of both extraction wells (located between Sandwich Road and Fisherman's Cove) and reinjection wells (located along the shore and as shallow wells upgradient of the withdrawal wells) to reduce the degree of short circuiting from the pond

to the pumping wells. The K-V plan called for withdrawal of 70 gallons per minute from two extraction wells with the water treated by spray irrigation in woods west of Sandwich Road. This treatment technology would be very appropriate and cost effective for phosphorus, but would not meet Superfund requirements for volatile organic compounds (VOCs) unless VOC concentrations were very low in the extracted ground water. Otherwise, an air stripper or other type of treatment system would be required to treat the withdrawn ground water. Under the K-V plan, an off-site well would be pumped to supply uncontaminated water for the reinjection wells.

The plume interception scheme is attractive in that it employs proven technology. Drawbacks are potential operational problems with reinjection wells, which tend to foul and become clogged, and the potential to reduce inflow to the pond. Modification of the system could correct some of these potential problems. For example, the USGS found the highest phosphorus concentrations farther away from the pond than the withdrawal well location proposed by K-V Associates. This raises the possibility that the withdrawal well locations proposed by K-V Associates could draw high phosphorus concentrations closer to the pond, creating worse problems if for some reason the system ceased to operate. If withdrawal wells were located at the zone of elevated phosphorus in the former gravel pit west of Sandwich Road, the highest concentrations of phosphorus would be removed and there would be less possibility of drawing contaminated ground water closer to the pond. Rather than injection wells along the lake shore, infiltration trenches, which require less maintenance, could be installed in the former gravel pit between the withdrawal wells and the pond. Location of withdrawal wells west of Sandwich Road would do little to address the current discharge to the pond because that part of the plume would be downgradient of the withdrawal wells. However, this system would prevent future discharges to the pond from becoming much worse and thus address what is probably the gravest threat to the pond.

Injection of hydrogen peroxide. This alternative was suggested by K-V Associates (1989) and entails pumping hydrogen peroxide into the aquifer to create an oxidized environment in which insoluble phosphorus compounds would precipitate. Hydrogen peroxide would be injected into the aquifer via selected wells within the USGS experimental array downgradient of the sewage beds in the abandoned gravel pit west of Sandwich Road. Hydrogen peroxide breaks down to produce water and oxygen and thereby would provide oxygen in the anoxic zone of the sewage plume. The proposed remediation presumes that with oxygen once again in the ground water, iron, manganese, and

phosphorus would precipitate, removing dissolved phosphorus from the flowing ground water.

This and other proposals based on restoration of aerobic conditions in the aquifer presume a unique relationship between anoxic conditions and elevated phosphorus concentrations and mobility. The recent USGS findings of elevated phosphorus in a suboxic zone calls this presumption into question and shows that the phosphorus chemistry is more complicated and less well understood than supposed previously. More significantly, the USGS column studies in which clean oxygenated water was passed through contaminated soil cores and liberated a spike of high phosphorus raises concerns that aquifer oxygenation could have an entirely contrary effect and free phosphorus rather than sequester it. For this reason, careful laboratory tests followed by field pilot tests would be essential prior to application of hydrogen peroxide injection.

If proven effective, implementation of hydrogen peroxide injection would require the construction and maintenance of a system to store, distribute, and inject the hydrogen peroxide. Intermittent injection may be adequate, and thus reduce maintenance and operation costs. Existing monitoring wells could be used as injection wells.

In-situ aeration (air sparging). This alternative is similar in concept to hydrogen peroxide injection but instead injects air into the aquifer to create an aerobic environment. Air sparging technology has been established over the last several years as an effective means to mobilize and remove volatile organic contaminants in ground water. In those instances, the operative principle is different than supposed here. In essence, air is bubbled through the ground water, acquiring and then removing volatile organic compounds as vapors. The technology is successful because volatile compounds are more efficiently removed in a vapor phase than in a dissolved phase. Air sparging has also been found in some instances to enhance biodegradation of organic compounds by introducing oxygen.

Application of air sparging to the MMR plume is not to remove contaminants, but simply to introduce oxygen. Despite this difference in purpose, the experience and technology development for air sparging remains entirely applicable. In this sense, air sparging is a proven technology. The technology is appropriate for unconsolidated geologic conditions with high permeability; the Ashumet Pond environs are ideal in this respect. On the other hand, the air sparging alternative is founded on the same presumption as the hydrogen peroxide alternative, namely that there is a unique relationship between

anaerobic conditions and phosphorus mobility. As stated above, this is now questionable in light of the recent USGS field data. As with hydrogen peroxide injection, this technology would need to be tested in the laboratory and field to confirm that it would be effective.

Even if proven an effective remediation alternative, the air sparging alternative could be somewhat expensive to implement and operate. Special construction is required for sparging wells and existing monitoring wells would not suffice. An air compressor and system of air lines would also need to be constructed and then operated and maintained. Thus, both capital and operation and maintenance expenses are higher for an air sparging system than for some of the other alternatives presented here.

Permeable reactive wall. The permeable reactive wall is a very new and yet to be proven technology for *in-situ* ground-water remediation developed at the University of Waterloo, Ontario, Canada. It entails the excavation of a section of aquifer that is then replaced with a permeable reactive material that degrades the contaminant of concern. A variation on the technology, known as the funnel-and-gate system, entails the additional installation of impermeable barriers to direct the flow of contaminated ground water into a relatively short section of reactive wall (Starr and Cherry, 1994). The reactive wall technology has received the most attention in the form of metallic iron reactive walls as a possible means to remediate chlorinated organic solvents (O'Hannesin *et al.*, 1993); however initial field tests in remediating solvents have been disappointing (Cherry, 1994a). Column tests by Prof. D.W. Blowes at the University of Waterloo have shown phosphorus removal by iron slag (Cherry, 1994b), suggesting an iron slag reactive wall may be effective in remediating the MMR plume. The USGS has proposed to test this technology at the MMR in its continuing research (Walter, 1994b).

The advantages of the permeable reaction wall are considerable. Initial installation may be expensive, particularly if a long and deep trench must be excavated. However, once installed and in place, the system is completely passive, with essentially no maintenance and operation expense. Other than ground-water monitoring, which is a requirement for any alternative, replacement of the reactive media is the only expense and that would be infrequent if required at all.

Injection of potassium permanganate. This alternative is suggested by remarks by John Cherry at a recent lecture on aquifer remediation in Boston (Cherry, 1994a). Prof. Cherry discussed the favorable properties of potassium permanganate for aquifer remediation. Potassium permanganate is a strong oxidant that is soluble in water. It

overcomes a basic problem in aquifer remediation, namely that contaminants must be caused to move out of soil pores in order to be treated. Permanganate instead goes to the contaminants: favorable diffusion gradients essentially force the compound to seek out contaminants. Permanganate is a recognized treatment for the removal of ferrous iron, such as found in the iron zone of the MMR plume, by promoting the formation of insoluble ferric hydroxides (Posselt and Weber, 1972). Phosphate coprecipitates and adsorbs to ferric hydroxides and thus would be removed simultaneously with the iron.

Injection of potassium permanganate is an unproved technology for ground water treatment and thus would require extensive testing prior to implementation. It suffers from the same possible flaw as hydrogen peroxide and air injection insofar as it addresses anoxic conditions (specifically, the iron zone) and may be ineffective for the suboxic zone where the highest phosphorus concentrations were found. This technology is similar to the hydrogen peroxide injection alternative insofar as its infrastructure requirements.

Injection of iron-EDTA solution. Kenneth Stollenwerk of the USGS has suggested this alternative based on the observation that iron precipitation on contaminated soil cores may coat phosphorus adsorbed to sand grains and render the phosphorus unavailable (Walter, 1994b). The concept is to inject precipitable iron into the aquifer to create the same type of coating. EDTA would be injected with the iron to act as a carrier to transport the iron into the aquifer.

EDTA is an abbreviation for ethylenediamine tetraacetate, a chelating agent that forms very strong complexes with metal ions, including iron. Stumm and Morgan (1981) indicate that iron precipitates do not form in the presence of EDTA except at high pH. Although pH is elevated in the sewage plume, it is not as high as the range given by Stumm and Morgan for iron precipitation. Thus, there is a question as to the mechanism by which iron would be liberated from the EDTA and be available to precipitate in the aquifer. In any case, the chemistry is complex and would need to be tested in the laboratory and the field before is could be implemented. The USGS intends to test this alternative in its proposed future studies.

Plume diversion strategies. Intensive water-level measurements made by the USGS show that the predominant direction of ground-water flow from the MMR wastewater disposal beds is to the south, past Ashumet Pond (Figure 2). Only the easternmost portion of the phosphorus plume is actually intercepted by the pond. The configuration of the water table and ground-water flow patterns suggest that relatively minor changes in the

water table could divert the part of the plume nearest Ashumet Pond toward the south and away from the pond. This could possibly be effected by a ground-water recharge trench along the west side of Sandwich Road or in the abandoned gravel pit west of the road. Because of the high transmissivity of the aquifer formation a substantial flow of water would be required to maintain sufficient head in the aquifer to divert the flow. A possible source of water could be the treated water produced by ground-water remediation systems for other areas on the MMR.

Evaluation of plume diversion schemes would require simulation of alternative locations and flow rates with a ground-water flow model. The USGS has developed a model of the area which could be applied to this purpose. The scheme is attractive in that it depends upon straightforward and proven technology. It would require minimal operation and maintenance expense if tied to other water-generating remedial actions on the MMR. If pumping were required, capital, operation, and maintenance costs would be higher, though still less than a pump-and-treat alternative in that treatment is not required.

Isolation of Fisherman's Cove Area. There is ample time to test and implement ground-water remediation alternatives before the highest concentrations of phosphorus reach Ashumet Pond and therefore this assessment of alternatives stresses ground-water remedies over lake restoration remedies. In the event that ground-water remediation comes too late or is unsuccessful, a possible strategy is to isolate the portion of the pond into which the plume discharges in order to preserve the water quality of the remainder of the pond. Although the phosphorus intrusion problem occurs in the general area of Fisherman's Cove, which is shallow and would be relatively easy to isolate, the area of greatest discharge appears to be somewhat to the north of the cove. This is an area of more open shoreline where the pond bottom drops off much more rapidly.

Isolation of a part of the pond is obviously difficult and permanent alteration of the pond beyond consideration. However, floating dikes constructed of a high-mil sheet of plastic hung from a line of floats have been successfully used as internal baffles in cooling ponds for power plants and could be feasible in Ashumet Pond. This construction would have the advantages of costing relatively little and not altering the pond permanently. Moreover a complete and perfect seal is unnecessary so long as the bulk of the phosphorus inflow is mitigated.

The implementation of an isolation scheme or any other in-lake alternative should necessarily be viewed as a temporary remedy while a permanent solution was sought for the ground water. The rate of phosphorus migration in the ground water, as discussed above, is so slow that it would require on the order of 15 to 30 years for the untreated phosphorus contamination to be flushed from the aquifer. During that entire time, phosphorus would continue to discharge to Ashumet Pond. Once introduced, phosphorus would remain in the pond, largely in pond-bottom sediments where it would be available for rerelease when the hypolimnion became anaerobic. Clearly, the threat of continued phosphorus introduction to the long-term health of the pond, or the disruption that would be posed by a long-term floating barrier, favor the mitigation of the phosphorous problem in the ground water versus in the pond.

SUMMARY OF REMEDIATION ALTERNATIVES

The lack of prior experience with remediating ground-water phosphorus plumes makes it difficult to recommend a single alternative for the MMR plume. Several of the technologies for *in-situ* ground-water treatment appear to have promise and a pump-and-treat system is always a feasible and proven backup alternative. The USGS's unexpected findings regarding the phosphorus chemistry imply that those alternatives which involve chemical immobilization of phosphorus are uncertain. Thus, the alternatives based on air sparging, reactive walls, or injection of hydrogen peroxide, permanganate, or iron-EDTA solutions would all require testing in the laboratory and the field prior to full-scale implementation. Absent conclusive and convincing field tests of these alternatives, we recommend the established and reasonably certain pump-and-treat technology.

There is an important distinction between remediating the phosphorus plume and remediating the seemingly similar organic contaminant plumes at the MMR. Remediating the organic contaminants in ground water is for practical purposes an all-or-nothing proposition under Superfund: the contaminants must be removed to very low concentrations for the remediation to be deemed effective. In contrast, any remediation of the phosphorus plume will have a directly proportional benefit in reducing the load of phosphorus to Ashumet Pond. Any actions which reduce the phosphorus in the plume are likely to be beneficially and thus effective. The consequences of not proceeding rapidly to test and implement phosphorus remediation in the ground water is a continued and likely worsening deterioration of the water quality of Ashumet Pond. While in-lake remediation measures are also possible, the most direct and efficient route to counteracting the effects of the phosphorus plume is to treat the phosphorus in the ground water.

RESPONSIBILITY FOR COST OF REMEDIATION

INTRODUCTION

This section provides a review of state and federal laws, regulations, and guidance potentially relevant to responsibility for remediating phosphorus in the MMR sewage plume. This section is not intended to provide legal advice and legal counsel should be sought for definitive interpretation on the question of legal responsibility for plume cleanup.

The most pertinent Federal statute for the MMR site is the Comprehensive Response Compensation and Liability Act (CERCLA), most commonly known as Superfund. CERCLA originally became law in 1980 and was significantly modified by the Superfund Amendments and Reauthorization Act (SARA) of 1986. Virtually all of the cleanup work now underway on the MMR is under the aegis of Superfund.

The basic operating principles of Superfund cleanup are established by the statute itself and its governing regulations, known as the National Contingency Plan (NCP, 1990). By definition, Superfund deals with releases of hazardous substances and requires that those releases be remedied. Elemental phosphorus is a hazardous substance because it is highly reactive but the phosphate forms of phosphorus dissolved in wastewater are not. In this sense, then, CERCLA would not require the cleanup of the phosphorus in the Ashumet Valley plume.

However, CERCLA also requires the cleanup of "pollutants and contaminants" distinct from "hazardous substances." The following definition of pollutants and contaminants from the National Contingency Plan emphasizes potentially hazardous characteristics, but does not specifically exclude nonhazardous pollutants:

> Pollutant or contaminant...shall include, but not be limited to, any element, substance, compound, or mixture, including disease-causing agents, which after release into the environment and upon exposure, ingestion, inhalation, or assimilation into any organism, either directly from the environment or indirectly by ingestion through food chains, will or may reasonably be anticipated to cause death, disease, behavioral abnormalities, cancer, genetic mutation, physiological malfunctions (including malfunctions in reproduction) or physical deformations, in such organisms or their offspring...For purposes of the NCP, the term pollutant or contaminant means any pollutant or contaminant that may present an imminent or substantial danger to public health or welfare.

This definition is sufficiently broad as to make phosphorus a pollutant or contaminant under Superfund. Two aspects of the definition are possibly operative. First, the eutrophied condition of the pond has already resulted in death of organisms in the pond (fish kills documented by K-V Associates, 1991). Second, because it poses a threat to the water quality of Ashumet Pond, the sewage plume also poses a danger to public welfare.

Arguments concerning the status of phosphorus as a pollutant or contaminant under CERCLA may be less than relevant however. The Ashumet Valley plume is not contaminated by phosphorus alone. Ground water in the plume is also contaminated by solvents and other hazardous substances, and thus falls under the requirements of CERCLA and SARA. CERCLA puts great stress on selection of a remedial action "that is protective of human health and the environment" (Section 121(b)(1)). As pointed out in the preamble to the National Contingency Plan, "the overarching mandate of the Superfund program is to protect human health and the environment from the current and potential threats posed by uncontrolled hazardous waste sites. This mandate applies to all remedial actions and cannot be waived" (NCP, 1990, pg. 8725). Significantly, this description of Superfund's purpose draws no distinction between the hazardous and nonhazardous threats posed by a Superfund site but simply states that the environment be protected from threats posed by a site.

Under Section 121(d)(2)(A)(ii) of CERCLA, hazardous substances, pollutants, and contaminants allowed to remain after cleanup must meet ARARs, "Applicable or Relevant and Appropriate Requirements." ARARs are drawn from federal, state, or local environmental laws and regulations which bear on "a hazardous substance, pollutant, contaminant, remedial action, location, or other circumstance found at a Superfund site" (NCP, 1990 [40 CFR 300.5]). The requirement to meet ARARs was added in the SARA amendments primarily as a means to define the required level of cleanup at Superfund sites. With respect to surface water, the SARA amendments specifically cite the standards of the Clean Water Act and state that Federal Water Quality Criteria must be met when found to be relevant and appropriate. ARARs do not apply strictly or solely to hazardous substances, as indicated by the language "or other circumstance" in the regulation. For example, if a Superfund cleanup will entail discharging wastewater from a ground-water treatment system to surface water, then the discharge must meet the requirements of the Clean Water Act for both hazardous and nonhazardous chemicals in the discharge flow.

In their analysis of the Ashumet Valley plume (Jordan Co., 1991), HAZWRAP identifies a number of ARARs, of which the following may be pertinent to phosphorus cleanup:

- Sole source aquifer designation under the federal Safe Drinking Water Act;
- Endangered species protection under the federal Endangered Species Act;
- Ambient Water Quality Criteria under the federal Clean Water Act;
- Massachusetts ground-water quality standards; and
- Massachusetts surface-water quality standards.

In addition, the following state law is potentially pertinent:

- Endangered species protection under the Massachusetts Endangered Species Act.

Potential ARARs for the Ashumet Valley ground-water contamination plume are evaluated below with specific attention to their potential relationship to Ashumet Pond.

FEDERAL ARARs

The entirety of Cape Cod, including the Ashumet Valley, is designated as a sole source aquifer under the federal Safe Drinking Water Act. This designation prohibits the use of federal funds for any project which would contribute to contamination of the aquifer. This prohibition typically affects construction of federal buildings or interstate highways and the Sole Source Aquifer program has limited effect as a Superfund ARAR (U.S. EPA, 1988).

Maximum contaminant levels (MCLs) under the Safe Drinking Water Act are frequently cited as ARARs in ground-water cleanups under Superfund. However, there is no MCL for phosphorus and therefore this aspect of the Safe Drinking Water Act is not pertinent to the phosphorus plume.

Previous studies of Ashumet Pond have not identified any federally designated endangered species. Therefore, the federal Endangered Species Act is not applicable as an ARAR.

The federal Clean Water Act requires the U.S. EPA to periodically develop and publish ambient water-quality criteria. These criteria address the potential effects of

various pollutants on aquatic life and human health and recommend maximum concentrations for individual pollutants to prevent adverse effects. Strictly, water-quality criteria have no force of law but are simply recommendations to the states, which set legal water-quality standards. As discussed above, however, SARA specifically cite water-quality criteria as ARARs for Superfund site remediation. The most recent update of the water quality criteria, published in 1986, is commonly called the Gold Book after the color of its cover (and to distinguish it from predecessor versions which were green, blue, and red.) The Gold Book (U.S. EPA, 1986) discusses the effects of phosphate phosphorus on eutrophication of fresh-water lakes and ponds, and states:

> To prevent the development of biological nuisances and to control accelerated or cultural eutrophication, total phosphates as phosphorus (P) should not exceed 50 µg/l in any stream at any point where it enters any lake or reservoir, nor 25 µg/l within the lake or reservoir.

Nevertheless, the Gold Book also states that a national criterion is "evolving" and that "no national criterion is presented for phosphate phosphorus for the control of eutrophication" but that the information above "should be considered." We were informed by the U.S. EPA Ecologic Risk Assessment Branch that work on a eutrophication-related criterion just began in early November 1994 although the eventual criterion may specify the concentration of chlorophyll-a rather than phosphorus (U.S. EPA, 1994).

STATE ARARs

Several state laws and regulations are potentially pertinent to the MMR sewage plume. The MMR sewage treatment plant is required to have a Ground Water Discharge Permit under the Massachusetts Clean Waters Act (Massachusetts General Laws Chapter 21, Sections 26 through 53). As stated in the pertinent regulations (Code of Massachusetts Regulations, Chapter 314, Section 5.07, abbreviated as 314 CMR 5.07) the effect of issuing a permit is "to allow, to the extent specified in the permit..., the permittee to discharge pollutants to ground waters of the Commonwealth." In order to preserve ground-water quality, the regulations specify maximum pollutant levels that may be discharged, but do not specifically list phosphorus (314 CMR 5.10). A generic requirement for "all other pollutants" prohibits discharge "in such concentrations which in the opinion of the Director [of the Division of Water Pollution Control] would impair the ground water for use as a source of potable water or cause or contribute to a condition in contravention of standards for other classified waters of the Commonwealth" (314 CMR 5.10(3)(b)). The regulations also prohibit the Massachusetts Department of Environmental Protection (DEP) from

issuing permits "when the discharge will cause or contribute to a condition in contravention of standards for classified waters of the Commonwealth" (314 CMR 5.06(1)).

The ground-water discharge regulations further specify at 314 CMR 5.19 that for all permits, "no discharge authorized in the permit shall result in a violation of the Massachusetts Surface Water Quality Standards (314 CMR 4.00) or the Massachusetts Ground Water Quality Standards (314 CMR 6.00)." The regulation goes on to define that a violation is determined to have occurred when concentrations measured in ground-water samples in a downgradient well exceed state ground-water quality criteria. In the event of permit violations, the regulations require under "Duty to Mitigate" that "the permittee shall take all reasonable steps to minimize or prevent any adverse impact to human health or the environment resulting from non-compliance with the permit" (314 CMR 5.19(7)).

Ground water at the MMR would qualify as Class I ground waters, fresh ground waters, under the Massachusetts ground-water quality standards (314 CMR 6.03). Water-quality criteria for Class I ground water do not include a specific criterion for phosphorus, although there is a general criterion for "all other pollutants" virtually identical to the condition described above for ground-water discharges. Thus, under these regulations phosphorus would be considered a ground-water pollutant to the extent that it contributes to surface-water pollution as manifested by exceeding surface-water quality standards or criteria.

Ashumet Pond is not explicitly classified in the surface-water quality standards regulations and thus is classified by default as Class B, High Quality Waters (314 CMR 4.06). The water-quality regulations pose no specific numerical criterion for phosphorus, but require in surface waters of all classes that nutrients "shall not exceed the site-specific limits necessary to control accelerated or cultural eutrophication" (314 CMR 4.05(5)(c)). Under the state antidegradation provisions (314 CMR 4.04), the quality of Class B waters must be protected and maintained unless limited degradation is specifically authorized by the Division of Water Pollution Control. The antidegradation regulations specifically address control of eutrophication at 314 CMR 4.04(5), covering both point-source discharges to surface water (i.e., from a discharge pipe) and non-point source discharges. The ground-water plume from the MMR constitutes a nonpoint source, and is therefore subject to the regulation's statement that "Activities which result in the nonpoint source discharge of nutrients to lakes and ponds shall be provided with all reasonable best management practices for nonpoint source control."

As discussed above, Massachusetts water-quality regulations do not provide a clear and explicit prohibition on phosphorus discharges above a certain concentration. Nevertheless, there is a clear progression in the regulations that makes protection of Ashumet Pond a responsibility of the MMR. This progression is as follows:

1. The discharge of phosphorus to Ashumet Pond is contributing to accelerated eutrophication and is therefore a violation of the narrative surface-water quality standards for prevention of eutrophication (314 CMR 4.05(5)(c)).

2. Because it causes surface-water quality violations, the phosphorus in the plume also violates ground-water quality standards. (314 CMR 6.06(1)(aa)).

3. Wastewater discharges which cause a violation of surface- or ground-water standards are not authorized by ground-water discharge permits (314 CMR 5.19(1)).

Finally, the intent of Superfund to restore contaminated ground water is clear and unequivocal. For example, the NCP states "EPA expects to return usable ground water to their beneficial uses whenever practicable..." For the Ashumet Valley plume, a primary beneficial use is discharge to Ashumet Pond.

Another potential state ARAR is the Massachusetts Endangered Species Act. Ashumet Pond is shown as habitat to listed rare species under the Massachusetts Endangered Species Act. An inquiry with the Massachusetts Natural Heritage and Endangered Species Program as to the species of concern has yet to be answered at the time of this writing.

REGULATORY REVIEW OF THE MMR WASTEWATER TREATMENT PLANT

Evaluation of the status of Massachusetts water-quality regulations as a Superfund ARAR necessarily entails understanding the regulatory history of the MMR wastewater treatment plant. For insight into the regulatory history of the MMR wastewater treatment plant, I reviewed the records of the Southeast Regional Office of the Massachusetts Department of the Environmental Protection. I was particularly interested in the conditions imposed by the plant's subsurface discharge permit and any possible past permit violations.

The wastewater treatment plant initially operated in an era when permits were not required. Amendments to the Massachusetts Clean Waters Act in 1973 extended jurisdiction of the state to include ground-water discharges, but it was not until September

18, 1981 that the Department of Environmental Quality Engineering (now DEP) sent a letter to Otis Air Force Base indicating that a subsurface discharge permit was required for the base wastewater treatment facility (McMahon, 1981). A permit application was submitted by the Air Force in October 1981 (Olson, 1981). A draft permit was issued in March 1984 on an interim basis while the plant was being upgraded. This permit limited the phosphorus in the effluent to 1 milligram per liter and required sampling for phosphorus on an annual basis. In October 1984, a final permit was issued, but without any limitation on phosphorus in the wastewater effluent (Appendix A of ANGSC, 1989). The requirement to monitor annually for phosphorus was retained. The permit also required a number of improvements to the treatment plant with a prescribed schedule.

A memorandum in the DEP file from the Air Force's engineering consultant to the Otis Air Force Base civil engineer (Donovan, 1985) discusses the deletion of the phosphorus requirement from the permit. He states:

> Phosphorus was considered for inclusion in the discharge permit but was not included after a review of groundwater quality data developed by the USGS showed little movement of phosphorus in the groundwater. USGS researchers believe that phosphorus is essentially all precipitated within 1,000 feet of the plant. DEQE officials stated that phosphorus will not be regulated for the foreseeable future and that planning should proceed without phosphorus removal.

At its closest point, Ashumet Pond is about 1600 feet from the nearest sand filter bed at the wastewater treatment facility.

The National Guard was slow to carry out the requirements of the 1984 discharge permit. An internal DEQE memorandum from 1986 (Sherman, 1986) discusses violations at the base and the possibility of future enforcement action. This was realized in October 1987 (Administrative Order, 1987) with the issuance of an administrative order to the U.S. Department of Defense and National Guard Bureau (referred to in the order as the "Respondents"). The order indicates its purpose is to establish a schedule to bring the facility into compliance and determine wastewater disposal alternatives. The order indicates that the facility had polluted over 18 billion gallons of potable ground water with detergents, phosphorus, nitrate, and other pollutants including hazardous chlorinated organic compounds. It also describes the history of permit violations, indicating numerous exceedences of permit limitations and ground-water quality standards, and failure to make improvements to the wastewater treatment facility. With respect to Ashumet Pond, the order states:

> The Respondents' discharges from the sewage treatment facility have resulted in discharges of pollutants to Ashumet Pond, a surface water of the Commonwealth. Further, the Respondents' discharges from the sewage treatment facility have caused the Massachusetts Surface Water Quality Standards to be exceeded in Ashumet Pond, a class B surface water. Ground water flowing into the Fisherman's Cove section of the pond has contained significantly elevated levels of total nitrogen and phosphorus concentrations. This nutrient enrichment has resulted in the prevalence of algal blooms in the pond and has created nuisance conditions. ... Further, the discharges from the sewage treatment facility have caused or contributed to accelerated eutrophication of the Ashumet Pond, numerous fish kills within the pond and the generation of noxious odors from the pond.

Further in the order, it is stated:

> The Respondents have violated permit condition 5.19(1), (2) and (4) by: a) causing the ground water downgradient of the sewage treatment facility to exceed the Massachusetts Groundwater Quality Standards... and b) causing waters of Ashumet Pond to exceed the Massachusetts Surface Water Quality Standards...by allowing the discharge of total nitrogen, total phosphorus, ammonia-nitrogen, sulfide, boron, iron, manganese and dissolved solids to the Fisherman's Cove section of the pond at such concentrations to adversely impact on the designated uses of this class B surface water of fishing and swimming.

The files of DEP, and particularly the 1987 administrative order, document a continuing pattern of permit violation and contravention of ground- and surface-water standards by the MMR wastewater treatment plant. This is significant with respect to Superfund actions because the record clearly establishes that the state has considered surface- and ground-water standards to be applicable at this site and to have been violated in the past. In essence, the records confirms these regulations to be ARARs and clarifies the applicability of imprecise narrative standards which could otherwise be subject to interpretation. The order also implies that aside from CERCLA action could be taken under the Massachusetts Clean Waters Act to force cleanup of the MMR plume.

ENVIRONMENTAL RISK ASSESSMENT

CERCLA provides that an environmental evaluation be conducted to determine if a Superfund site threatens the environment (NCP, 1990, 40 CFR 300.430(e)(2)(i)(G)). The requirement to protect the environment is significant with respect to the Ashumet Valley plume cleanup and protection of Ashumet Pond.

Guidance for environmental evaluation under Superfund (U.S. EPA, 1989) discusses assessment of "contaminants" without specific restriction to hazardous chemicals. Other nonhazardous considerations are also discussed; for example, under "Evaluation of Potentially Affected Habitats", the guidance document lists physical disruption of habitat as a potential effect of Superfund sites (U.S. EPA, 1989, page 43). The guidance lays out a procedure for ecological assessment of Superfund sites that considers the physical, chemical, and biological structure of affected habitat. The end result of an environmental evaluation is the determination of the threat posed by the site to the environment. This information is then used to determine is remedial action is required to protect the environment. An preliminary environmental evaluation has been completed for the southern part of the Ashumet Valley plume (HAZWRAP, 1991) but not Ashumet Pond. The information currently being gathered under the Ashumet-Johns Pond Study would provide a basis for an assessment of Ashumet Pond.

CLEANUP OF NONHAZARDOUS SUBSTANCES AT OTHER SUPERFUND SITES

There are few Superfund sites which provide a precedent for cleanup of phosphorus in ground water. Inquiry with the U.S. EPA Records of Decision Hotline (RODS Hotline, 1994) found only three sites at which phosphorus is named. A Record of Decision is required to be written whenever the EPA selects a remedial action for a Superfund site or part of site. The Record of Decision describes the site, its history and contamination, the remedial actions considered, and the reasons for selection of a particular action. In answering our inquiry, RODS Hotline personnel searched the Records of Decision System, a database of all RODS. A keyword search of 1,114 Records of Decision found only the following sites involving phosphorus:

> Keystone Sanitary Landfill, Hanover, Pennsylvania. This is an unlined sanitary landfill which accepted household, municipal, industrial, and construction wastes including phosphorus-contaminated sand. The cleanup included a leachate collection and on-site spray irrigation system to contain contaminated ground water on site. The primary contaminants of concern were volatile organic compounds and phosphorus was not included as a ground-water analysis parameter or as a factor in the cleanup (U.S. EPA, 1990).
>
> Aberdeen-Edgewood Site, Aberdeen Proving Grounds, Aberdeen, Maryland. This is a military ordnance site contaminated by a variety of chemical-warfare agents including white phosphorus. White phosphorus is a very toxic and flammable form of elemental phosphorus.

> Northern Engraving Corporation, Sparta, Wisconsin. This is a manufacturing facility that produces metal parts for the automobile industry. About 900 cubic yards of sludge contaminated by phosphorus and a variety of metals were disposed of on the site and were required to excavated, stabilized, and disposed in an on-site hazardous waste landfill. The Record of Decision discusses ARAR concentration limits for chlorinated solvents, fluoride, copper, nickel, and zinc but not phosphorus (U.S. EPA, 1987).

Another potentially precedential site is the Baldwin Park Operable Unit of the San Gabriel Basin Superfund Site in Los Angeles County, California. An extensive area of ground water in the San Gabriel Aquifer Basin is contaminated by chlorinated organic solvents from numerous industries in the area around Baldwin Park, California. The Feasibility Study (FS) for the Baldwin Park Operable Unit calls for cleanup of both these hazardous organic chemicals and high concentrations of nitrate (CH2M HILL, 1993). The FS indicates that nitrate concentrations have been elevated since the 1950s, but does not indicate the source of the contamination. On-site septic systems, agricultural fertilizers, and industry may all cause nitrate contamination. Nitrate is not a hazardous substance under Superfund but is a listed drinking-water contaminant under the Safe Drinking Water Act for which there is a Maximum Contaminant Level. The FS calls for cleanup of nitrate to below the MCL in water extracted as a part of the ground-water remedy because some of the water is planned for subsequent use as drinking water. In this instance, the requirement to clean up a nonhazardous chemical derives from its intended use rather than as a strict ground-water cleanup requirement. Nonetheless, there is a possible parallel to the Ashumet Valley plume where part of the "use" of the ground water is discharge to Ashumet Pond.

SUMMARY OF REMEDIATION RESPONSIBILITY

A review of the CERCLA statute and regulations shows a clear requirement to correct the adverse effects of Superfund sites on the environment without restriction to problems caused only by hazardous substances. Because the MMR is a Superfund site and also because the wastewater treatment plant ground-water contamination plume contains hazardous substances, CERCLA requires remedial action to mitigate the threat posed to Ashumet Pond by the plume, whether from phosphorus, hazardous substances, or other nonhazardous substances.

There is also a history of violations by the MMR wastewater treatment plant of the Massachusetts Clean Waters Act and the subsurface discharge permit. Past enforcement

actions have required the National Guard to correct problems with the wastewater treatment plant design. Similar actions could be initiated to force correction of the ground- and surface-water quality standards violations caused by sewage plume. In addition, the Massachusetts water-quality standards are subsumed by CERCLA as ARARs, “applicable or relevant and appropriate requirements” and thus must be addressed by CERCLA remedial action.

CONCLUSIONS AND RECOMMENDATIONS

CONCLUSIONS

1. Disposal of treated wastewater via sand-filter beds at the Massachusetts Military Reservation wastewater treatment plant has created a plume of sewage-contaminated ground water that extends 11,000 feet south from the infiltration beds.

2. The MMR sewage plume is contaminated by phosphorus, total dissolved solids, chloride, sodium, boron, detergents, hazardous organic compounds, and various chemical forms of nitrogen.

3. The MMR infiltration beds are located at their nearest point approximately 1600 feet upgradient of Ashumet Pond; part of the MMR plume discharges to Ashumet Pond along a reach of shoreline north of Fisherman's Cove, producing visual evidence of contamination in black, manganese-stained rocks and growth of attached algae.

4. Phosphorus is an essentially nutrient for algal growth. When introduced into freshwater lakes and ponds in excessive quantities, phosphorus can lead to an overabundance of algae, a condition known as eutrophication which is characterized by degraded water quality.

5. Ashumet Pond is currently a mesotrophic lake but is threatened with worsening water quality due to inflow of phosphorus from the MMR sewage plume.

6. Recent studies by the U.S. Geological Survey have discovered a zone within the MMR plume upgradient of Ashumet Pond in which phosphorus is found at concentrations up to 6 mg/l, three times higher than any previously observed ground-water concentrations in the aquifer.

7. Conventional theory is that phosphorus is immobile in ground water except under anaerobic conditions, under which phosphorus migrates at a much slower rate than the speed of ground water. The recent findings by the U.S. Geological Survey call into question accepted theories of phosphorus behavior in ground water because the high phosphorus concentrations coexist with low but nonzero concentrations of dissolved oxygen.

8. Laboratory column studies by the U.S. Geological Survey showed a sudden liberation of phosphorus from sewage-contaminated soil cores following the inflow of clean water after a period of prior inflow of sewage-contaminated water.

9. The MMR plume upgradient of Ashumet Pond has experienced a similar transition from sewage-contaminated flow to clean flow following the abandonment of the MMR wastewater infiltration beds nearest Ashumet Pond. The high phosphorus concentrations observed in the plume may be the result of phosphorus liberation similar to that seen in the laboratory columns.

10. The newly discovered zone of elevated phosphorus concentrations represents a potentially serious threat to Ashumet Pond in that it could migrate to the pond and greatly increase the quantity of phosphorus entering the pond.

11. The mobility of the elevated phosphorus concentrations is uncertain, but it could take as little as 5 years for significantly increased levels of phosphorus to reach Ashumet Pond.

12. Comparison of data collected during water quality surveys in 1980, 1985-86, and 1992-94 does not show any definitive trends over time in the water quality of Ashumet Pond.

13. Measurements of ground-water inflow to Ashumet Pond from the MMR plume show increased concentrations of phosphorus in 1993 versus 1985-86.

14. Approximately one half of the phosphorus currently reaching Ashumet Pond comes from the MMR plume. Absent the MMR pollutant load, Ashumet Pond would likely be an oligotrophic lake.

15. Projections of future increases in the amount of phosphorus reaching Ashumet Pond from the MMR plume forecast a transition to eutrophic and possibly hypereutrophic conditions if steps are not taken to control phosphorus intrusion from the MMR plume.

16. The most efficient, cost-effective, and protective strategy for correcting the effects of the MMR plume on Ashumet Pond is to remediate the phosphorus in the ground water before it reaches the pond.

17. A variety of potential *in-situ* remedial alternatives to treat phosphorus in the MMR plume have been proposed. All would require laboratory and field testing prior to implementation.

18. In the event that *in-situ* treatment technologies prove ineffective, a pump-and-treat system to remove phosphorus contaminated ground water is a proven and straightforward backup alternative.

19. Any action that reduces the phosphorus reaching Ashumet Pond will produce a beneficial effect on the pond's water quality.

20. It is of utmost importance that the necessary research and tests be commenced as soon as possible in order to ensure that corrective measures can be taken before significantly higher concentrations of phosphorus reach Ashumet Pond.

21. There is a clear requirement under the Superfund act to control the adverse effects of Superfund sites on the environment. This requirement does not distinguish between effects of hazardous and nonhazardous substances and thus applies to the control of the MMR phosphorus plume.

22. The Commonwealth of Massachusetts has cited the MMR wastewater treatment plant in the past for violations of surface- and ground-water quality standards because of the ground-water plume and its effects on Ashumet Pond. Correction of the MMR plume is therefore actionable under the Massachusetts Clean Waters Act as well as the federal Superfund act.

RECOMMENDATIONS

The following are recommendations for consideration by the Ashumet Valley Property Owners Association:

- Further work is needed to understand the chemistry and transport of the ground-water phosphorus plume and how it can be remediated by *in-situ* techniques. Better understanding is essential to developing effective measures to remediate phosphorus in the ground water. The Association should encourage the National Guard Bureau to continue and accelerate this work as a part of the environmental restoration program.

- New information on ground-water and lake quality points to the ongoing and potentially accelerating deterioration of the pond. The Association should encourage the National Guard Bureau to begin evaluation, testing, and implementation of ground-water remediation alternatives as soon as possible.

- There should be a continuing program of surface-water quality monitoring to assess the trophic state of Ashumet Pond. The plume of sewage-contaminated ground water from the MMR sewage treatment plant is likely to undergo significant changes in ground-water chemistry over the next several years following the cessation of sewage disposal. This creates the potential to increase an already significant source of phosphorus to Ashumet Pond and accelerate the rate of eutrophication of the pond. Therefore, the Association should encourage the National Guard Bureau to sponsor a program of continuing regular monitoring of trophic state indicators in the pond.

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Appendix A

Summary of Ashumet Pond Water-Quality Data

	8/13/80	4/22/85	5/4/85	5/23/85	6/3/85	6/13/85	6/21/85	7/1/85	7/12/85	7/22/85	8/1/85	8/12/85	8/27/85
Station 1													
Epilimnion													
Chlorophyll-a (mg/l)		1.15	2.3	0.85	0.7		4.3		2.05				2
Secchi disk transparancy (m)	2.4									2.7			3.0
Total phosphorus (mg/l)	0.01			0.010			.0.009			0.005		0.016	0.007
Dissolved phosphorus (mg/l)				0.006			0.005			0.005		0.008	<0.005
Soluble reactiva phosphorus (mg/l)													
Matalimnion (9 m)													
Total phosphorus (mg/l)				0.007			0.017			0.016		0.028	0.013
Dissolved phosphorus (mg/l)				<0.005			0.011			0.016		0.017	0.013
Soluble reactive phosphorus (mg/l)													
Hypolimnion													
Total phosphorus (mg/l)				0.009			0.021			0.042		0.015	0.133
Dissolved phosphorus (mg/l)				0.005			0.021			0.042		0.011	0.131
Solubla reactive phosphorus (mg/l)													
Dissolved Oxygan (mg/l)	0					3.6		0.2			0.2		2.2
Total Diatoms													
Achnanthes sp.													
Asterionella formosa													
Cyclotella sp.													
Fragilaria crotonensis													
Melosira sp.													
Melosira italica													
Navicule sp.													
Nitzschia sp.													
Rhizosolenie ariansis													
Stephenodiscus niagrare													
Synedra sp.	112												
Tabellaria fenestra													
Subtotal	112												
Grean algae													
Ankyra judayi													
Arthrodesmus sp.													
Chlamydomonas sp.													
Chlorogonium sp.													
Coelastrum sp.	28												
Elakatothrix geletinosa													
Eudorina elegens													
Golenkinia radieta													
Kirchneriella contorta													
Mougeotia sp.													
Pediastrum boryanum													
Scenedesmus sp.													
Sphaerocystis sp.	364												
Spyrogyra													
Staurastrum sp.	28												
Tetraedron minimum													
Tetrastrum staurogeniaforme													
Treubaria setigera													
Subtotal	420												
Cryptophytes													
Cryptomonas sp.	56												
Cryptomonas erosa													
Cryptomonas marssonii													
Katablepharis ovalis													
Rhodmonas minuta													
Subtotal	56												
Blue-green algae													
Anabeana sp.													
Anacystis sp.	224												
Aphanocapsa sp.													
Dactypococcopsis acicularis													
Oscillatoria limnetica													
Subtotal	0												
Golden-brown algae													
Chromulina sp.													
Chrysamoeba sp.													
Chrysochromulina parva													
Dinobryon sp.													
Kephyrion sp.													
Mallomonas sp.													
Ochromonas sp.													
Ophiocytium capitatum													
Pseudopedinella arkensis													
Synura adamsii													
Subtotal													
Othar													
Phacus sp.													

	8/13/80	4/22/85	5/4/85	5/23/85	6/3/85	6/13/85	6/21/85	7/1/85	7/12/85	7/22/85	8/1/85	8/12/85	8/27/85
Caratium hirundinella													
Glanodinium sp.													
Gymnodinium sp.													
Peridinium sp.													
Chromuline sp.													
Microflegellates													
Subtotal													
Totel cell count	588												
Station 2													
Chlorophyll-a (mg/l)		2.6	2.65	2.2	1.9		3.75		4	0.9			1.75
Secchi disk trensperency (m)													
Totel phosphorus (mg/l)				0.025			0.041			0.053		0.042	0.046
Dissolved phosphorus (mg/l)				0.015			0.041			<0.005		0.033	0.046
Soluble reective phosphorus (mg/l)													
Stetion 3													
Chlorophyll-e (mg/l)							1.5			1.9			1.45
Secchi disk transperency (m)										2.3			2.7
Totel phosphorus (mg/l)				0.012			0.013			0.023			0.011
Dissolved phosphorus (mg/l)				0.005			0.011			0.015			0.009
Soluble reectivе phosphorus (mg/l)													
Phytoplenkton (#/ml):													
Total Dietoms													
Achnanthes sp.													
Asterionelle formosa													
Cyclotelle sp.													
Fragilena crotonensis													
Gyrosigme sp.													
Melosira sp.													
Melosira italica													
Nitzschia sp.													
Rhizosolenia eriensis													
Stephanodiscus niagrare													
Synedra sp.													
Tebelleria fenestra													
Subtotal													
Green elgae													
Ankyra judeyi													
Arthrodamus sp.													
Chlamydononas sp.													
Chlorogonium sp.													
Closterium sp.													
Coelastrum sp.													
Dictyosphaenum pulchellum													
Eudorina elegans													
Golenkinia radiata													
Monoraphidium setiforme													
Pediastrum duplex													
Scenedesmus sp.													
Schizochlamys gelatinosa													
Sphaerocystis sp.													
Spyrogyra													
Staurastrum sp.													
Tetrahedron minimum													
Tetrastrum staurogeniaforma													
Subtotal													
Cryptophytes													
Cryptomonas ssp.													
Cryptomonas erosa													
Cryptomonas marssonii													
Cryptomonas rostratifons													
Katablephans ovalis													
Rhodmonas minuta													
Subtotal													
Blue-green algae													
Anecystis sp.													
Aphanocapse sp.													
Dactypococcopsis eciculans													
Oscilletorie sp.													
Subtotel													

	8/13/80	4/22/85	5/4/85	5/23/85	6/3/85	6/13/85	6/21/85	7/1/85	7/12/85	7/22/85	8/1/85	8/12/85	8/27/85
Golden-brown algae													
Chromulina sp.													
Chrysamoeba sp.													
Chrysochromulina parva													
Dinobryon sp.													
Kephyrion sp.													
Mallomonas sp.													
Ochromonas sp.													
Ophiocytium capitatum													
Pseudopedinella arkansis													
Synura adamsii													
Subtotel													
Other													
Phacus sp.													
Peridinium sp.													
Caratium hirundinella													
Glanodinium sp.													
Gymnodinium sp.													
Trachalomonas sp.													
Chromulina sp.													
Microflegelletes													
Other													
Totel cell count													
Stetion 4													
Chlorophyll-a (mg/l)		2.05		0.55			4.9			1.45			1
Secchi disk transperency (m)										2.7			3.2
Total phosphorus (mg/l)				0.008						<0.005			0.007
Dissolved phosphorus (mg/l)				0.005						<0.005			<0.005
Soluble reective phosphorus (mg/l)													

	9/26/85	10/24/85	11/26/85	12/2/85	12/30/85	1/21/86	2/20/86	2/25/86	3/21/86	4/1/86	4/11/86	4/18/86	5/1/86
Station 1													
Epilimnion													
Chlorophyll-a (mg/l)	1.1	1.05		1.7	1.05	4.4		5.94					
Secchi disk transparency (m)	3.7	3.7			4.3	4.8		4.6	3.0		2.7		3.0
Total phosphorus (mg/l)	<0.005	<0.005	0.014		0.038	0.016		0.014	0.009	0.01	0.019		
Dissolved phosphorus (mg/l)	<0.005	<0.005	0.008		0.032	0.015		0.005	0.005	0.005	0.006		
Soluble reactive phosphorus (mg/l)													
Metalimnion (9 m)													
Total phosphorus (mg/l)	0.023	<0.005								0.016	0.014		
Dissolved phosphorus (mg/l)	0.022	<0.005								0.005	0.006		
Soluble reactive phosphorus (mg/l)													
Hypolimnion													
Total phosphorus (mg/l)	0.059	<0.005				0.016		0.022	0.073	0.015	0.013		
Dissolved phosphorus (mg/l)	0.049	<0.005				0.016		0.005	0.033	0.005	0.005		
Soluble reactive phosphorus (mg/l)													
Dissolved Oxygen (mg/l)		5	10.9			12.6	13		13.3		10.9	7.9	
Total Diatoms													
Achnanthes sp.													
Asterionella formosa													
Cyclotella sp.													
Fragilaria crotonensis													
Melosira sp.													
Melosira italica													
Navicula sp.													
Nitzschia sp.													
Rhizosolenia eriensis													
Stephanodiscus niagrara													
Synedra sp.													
Tabellaria fenestra													
Subtotal	1110	410	320			490		920	2270		1230		240
Green algae													
Ankyra judayi													
Arthrodesmus sp.													
Chlamydomonas sp.													
Chlorogonium sp.													
Coelastrum sp.													
Elakatothrix gelatinosa													
Eudorina elegans													
Golenkinia radiata													
Kirchneriella contorta													
Mougeotia sp.													
Pediastrum boryanum													
Scenedesmus sp.													
Sphaerocystis sp.													
Spyrogyra													
Staurastrum sp.													
Tetraedron minimum													
Tetrastrum staurogeniaforme													
Treubaria setigera													
Subtotal	40	40	40			20		110	60		50		90
Cryptophytes													
Cryptomonas sp.													
Cryptomonas erosa													
Cryptomonas marssonii													
Katablepharis ovalis													
Rhodomonas minuta													
Subtotal													
Blue-green algae													
Anabaena sp.													
Anacystis sp.													
Aphanocapsa sp.													
Dactypococcopsis acicularis													
Oscillatoria limnetica													
Subtotal	260	120	120			20		30	100		30		50
Golden-brown algae													
Chromulina sp.													
Chrysamoeba sp.													
Chrysochromulina parva													
Dinobryon sp.													
Kephyrion sp.													
Mallomonas sp.													
Ochromonas sp.													
Ophiocytium capitatum													
Pseudopedinella erkensis													
Synura adamsii													
Subtotal													
Other													
Phacus sp.													

	9/26/85	10/24/85	11/26/85	12/2/85	12/30/85	1/21/86	2/20/86	2/25/86	3/21/86	4/1/86	4/11/86	4/18/86	5/1/86
Ceratium hirundinella													
Glenodinium sp.													
Gymnodinium sp.													
Peridinium sp.													
Chromulina sp.													
Microflagellates													
Subtotal	0	30	0			60		70	60		30		70
Total cell count	1410	600	530			590		1130	2490		1340		450
Station 2													
Chlorophyll-a (mg/l)	2	2.15		2.85	2	3		7.03					
Secchi disk transparency (m)													
Total phosphorus (mg/l)	0.005	<0.005	0.013		0.032	0.015	0.025		0.016	0.014	0.021		
Dissolved phosphorus (mg/l)	0.005	<0.005	0.008		0.028	0.014	0.006		0.012	0.009	0.012		
Soluble reactive phosphorus (mg/l)													
Station 3													
Chlorophyll-a (mg/l)	1.6	1.4		1.45	1.2	0.65							
Secchi disk transparency (m)	3.4	3.2			2.4	3.4			1.8		2.4		
Total phosphorus (mg/l)	0.006	<0.005	0.012		0.009	0.015	0.017		0.014		0.014		
Dissolved phosphorus (mg/l)	0.006	<0.005	0.011		0.009	0.015	0.01		0.005		.0.006		
Soluble reactive phosphorus (mg/l)													
Phytoplankton (#/ml):													
Total Diatoms													
Achnanthes sp.													
Asterionella formosa													
Cyclotella sp.													
Fragilaria crotonensis													
Gyrosigma sp.													
Melosira sp.													
Melosira italica													
Nitzschia sp.													
Rhizosolenia eriensis													
Stephenodiscus niegrara													
Synedra sp.													
Tabellaria fenestra													
Subtotal	1110	410	320			490	920		2270		1230		
Green algae													
Ankyra judayi													
Arthrodemus sp.													
Chlamydononas sp.													
Chlorogonium sp.													
Closterium sp.													
Coelastrum sp.													
Dictyosphaerium pulchellum													
Eudorina elegans													
Golenkinia radiata													
Monoraphidium setiforme													
Pediastrum duplex													
Scenedesmus sp.													
Schizochlamys gelatinosa													
Sphaerocystis sp.													
Spyrogyra													
Staurastrum sp.													
Tetrahedron minimum													
Tetrastrum staurogeniaforma													
Subtotal	40	20	90			20	110		60		50		
Cryptophytes													
Cryptomonas ssp.													
Cryptomonas erosa													
Cryptomonas marssonii													
Cryptomonas rostratiforis													
Katablepharis ovalis													
Rhodmonas minuta													
Subtotal													
Blue-green algae													
Anacystis sp.													
Aphanocapsa sp.													
Dactypococcopsis aciculeris													
Oscillatoria sp.													
Subtotal	260	120	120			20	30		100		30		

	9/26/85	10/24/85	11/26/85	12/2/85	12/30/85	1/21/86	2/20/86	2/25/86	3/21/86	4/1/86	4/11/86	4/18/86	5/1/86
Golden-brown algae													
Chromuline sp.													
Chrysemoebe sp.													
Chrysochromulina parva													
Dinobryon sp.													
Kephyrion sp.													
Mellomones sp.													
Ochromones sp.													
Ophiocytium capitatum													
Pseudopedinella erkensis													
Synura adamsii													
Subtotal													
Other													
Phacus sp.													
Peridinium sp.													
Ceratium hirundinella													
Glenodinium sp.													
Gymnodinium sp.													
Trachelomonas sp.													
Chromulina sp.													
Microflagellates													
Other	0	30	0			60	70		60		30		
Total cell count	1410	630	530			590	1130		2490		1340		
Stetion 4													
Chlorophyll-a (mg/l)	0.95				1.4	0.5							
Secchi disk transparency (m)	4.1	4.3	3.6		3.4	3.5			3.0				
Total phosphorus (mg/l)	0.017	<0.005			0.011	0.016	0.017		0.010				
Dissolved phosphorus (mg/l)	0.007	<0.005			0.009	0.015	0.014		0.005				
Soluble reactive phosphorus (mg/l)													

	7/1/86	11/11/92	4/14/93	6/29/93	8/3/93	12/5/93	4/21/94	6/28/94	9/20/94	85-86 Average	92-94 Average
Station 1											
Epilimnion											
Chlorophyll-a (mg/l)		19.3	13.4	2.1	4.8	10.7	4.7	13.4	24.6	2.20	11.63
Secchi disk transparency (m)			2.4	7.2	4.1	3.0	3.4	2.8		3.56	3.80
Totel phosphorus (mg/l)						0.0199	0.0074	0.0145	0.0203	0.014	0.016
Dissolved phosphorus (mg/l)		0.00771	0.00231	0.00517	0.00461	0.0101	0.0071	0.0067	0.0035	0.0091	0.0059
Soluble reactive phosphorus (mg/l)		0.001	0.00062	0	0.00094	0.0026	0.0014	0	0.0038		0.0013
Metelimnion (9 m)											
Total phosphorus (mg/l)						0.0203	0.0097	0.0319	0.0084	0.0168	0.0176
Dissolved phosphorus (mg/l)		0.00743	0.00205	0.00881	0.00558	0.0095	0.0062	0.0088	0.0123	0.0129	0.0076
Soluble reactive phosphorus (mg/l)		0.001	0.00077	0.00082	0.00011	0.0022	0.0003	0	0.0028		0.0010
Hypolimnion											
Total phosphorus (mg/l)					0.00173	0.0173	0.0106	0.1609	0.0121	0.038	0.0405
Dissolved phosphorus (mg/l)		0.01029	0.00359	0.1802	0.2739	0.0082	0.0085	0.1198	0.0668	0.0294	0.0839
Soluble reactive phosphorus (mg/l)		0.00114	0.00062	0.23745	0.3761	0.0029	0.011	0.127	0.4285		0.1481
Dissolved Oxygen (mg/l)		2.2	9.61	0	0	9.4	5	0.1	0	7.25	3.29
Total Dietoms											
Achnanthas sp.				25				62.5			44
Asterionalla formose		80	3489.6	20		1095		159.1	18.4		810
Cyclotelle sp.		60	416.7						166.7		214
Fragilaria crotonensis		150									150
Melosira sp.		60							625		343
Malosira italice											
Nevicule sp.					41.7						42
Nitzschia sp.		5	468.8								237
Rhizosolenia eriensis		420			416.7			83.3	41.7		240
Stephanodiscus niagrare		355				31					193
Synedra sp.		5	31.3		166.7			6.1	30.6		48
Tabellaria fenestra		510					417	177.4	250.9		339
Subtotal		1645	4406.4	45	625.1	1126	417	488.4	1133.3	874	1236
Green algee											
Ankyra judayi			83.3		212.5			83.3			126
Arthrodesmus sp.			10.4								10
Chlamydomonas sp.				60					250		155
Chlorogonium sp.											
Coelestrum sp.								333.3			333
Elekatothrix gelatinose			83.3								83
Eudorina elegans					196.1			333.3	195.8		242
Golankinia radieta									83.3		83
Kirchneriella contorta									166.7		167
Mougeotia sp.									208.3		208
Pediastrum boryanum								0.4			0
Scenedesmus sp.		40	4666.7	40		250	2125		1666.7		1465
Sphaerocystis sp.											
Spyrogyra											
Steurastrum sp.		5	10.4					0.8			5
Tatraedron minimum						83	531				307
Tetrastrum staurogeniaforme								1700			1700
Treubaria setigera									83.3		83
Subtotal		45	4854.1	100	408.6	333	2656	2451.1	2654.1	63	1688
Cryptophytes											
Cryptomonas sp.		90	52.1	10		171		187.5			102
Cryptomonas erosa				13					83.33		48
Cryptomonas marssonii		5		3	41.7		106	62.5			44
Keteblephens ovalis		200	666.7	240	212.5	1583	319	62.5	333.3		452
Rhodmonas minuta		40	1000	840	212.5	833	531	166.7	1333.3		620
Subtotal		335	1718.8	1106	466.7	2587	956	479.2	1749.93		1175
Blue-green algae											
Anabaana sp.								16.7			17
Anecystis sp.											
Aphanocapsa sp.			61583.3		12750				9333.3		27889
Dactypococcopsis acicularis			541.7	100			1333	41.7	750		553
Oscilletoria limnetica			72.9		24.5				24.5		41
Subtotal			62197.9	100	12774.5	0	1333	58.4	10107.8	91	12367
Golden-brown algae											
Chromulina sp.								62.5			63
Chrysamoeba sp.					212.5						213
Chrysochromulina parva		140	1750	3320	850	7083	2656	1912.5	2083.3		2474
Dinobryon sp.		100	510.4		4.2			8.8	189.7		163
Kephyrion sp.			916.7		212.5						565
Mallomonas sp.			20.8		41.7						31
Ochromonas sp.			166.7		2125				83.3		792
Ophiocytium capitatum			250								250
Psaudopedinella erkensis			333.3	80							207
Synura adamsii		490									490
Subtotal		730	3947.9	3400	3445.9	7083	2656	1983.8	2356.3		3200
Other											
Phacus sp.											

	7/1/86	11/11/92	4/14/93	6/29/93	8/3/93	12/5/93	4/21/94	6/28/94	9/20/94	85-86 Avaraga	92-94 Avaraga
Caratium hirundinella								1.7			2
Glanodinium sp.		15		10	41.7						22
Gymnodinium sp.				20	0.4				41.7		21
Pandinium sp.									0.8		1
Chromulina sp.											
Microflagallatas		80	83.3	20	17212.5	1333	3188	10879.2	1416.7		4277
Subtotal		95	83.3	50	17254.6	1333	3188	10880.9	1459.2	40	4293
Total cell count		2850	77208.4	4801	34975.4	12462	11206	16341.8	19460.6	1068	22413
Station 2											
Chlorophyll-a (mg/l)		17.1	8	1.6	4.7	13.4	3.3	3.2	34.7	2.77	10.75
Secchi disk transparancy (m)			2.9	7.2	4.1		3.1	2.5			3.94
Total phosphorus (mg/l)						0.0232	0.0118	0.0083	0.0121	0.027	0.014
Dissolved phosphorus (mg/l)		0.00743	0.00462	0.00372	0.0141	0.0098	0.0065	0.0101	0.0163	0.0191	0.0091
Solubla raactiva phosphorus (mg/l)		0.00086	0.00062	0.00005	0.00227	0.0026	0.0008	0	0.0031		0.0013
Station 3											
Chlorophyll-a (mg/l)		16	10.7	2.1	4	8	4.7	1.1	20.3	1.39	8.36
Secchi disk transparancy (m)		4.5	2.8		3.9		3.0	2.5		2.70	3.33
Total phosphorus (mg/l)						0.0173	0.0097	0.0055	0.0168	0.013	0.012
Dissolved phosphorus (mg/l)		0.00914	0.00308		0.00412	0.0092	0.0068	0.0078	0.0114	0.0093	0.0074
Solubla raactiva phosphorus (mg/l)		0.00157	0.00062	0.00469	0.00094	0.0021	0.001	0	0.0026		0.0017
Phytoplankton (#/ml):											
Total Diatoms											
Achnanthes sp.								83.3			83
Astarionalla formosa		80	4854.2	4		1354	239	140.7	42.8		959
Cyclotella sp.		20	416.7						83.3		173
Fragilaria crotonensis											
Gyrosigma sp.								0.4			0
Malosira sp.				1					342.6		172
Malosira italica											
Nitzschia sp.		2.5	20.8				6				10
Rhizosolenia ariansis		240			354.2			166.7	125		221
Stephanodiscus niagrare		132.5				80					106
Synedra sp.		107.5	166.7	5	125			6.1	41.7		75
Taballaria fenastra						271	385	165.2	250.9		268
Subtotal	240	582.5	5458.4	10	479.2	1705	630	562.4	886.3	874	1289
Graan algae											
Ankyra judayi						83		41.7			62
Arthrodamus sp.								6.1			6
Chlamydononas sp.				40					83.3		62
Chlorogonium sp.		10		20							15
Clostarium sp.							6				6
Coelastrum sp.											
Dictyosphaarium pulchellum			1333.3						250		792
Eudonna elegans								6.7			7
Golankinia radiata				20							20
Monoraphidium satiforma			833.3								833
Pediastrum duplax									6.1		6
Scenedesmus sp.		20	3833.3		425		956		750		1197
Schizochlamys gelatinosa									166.7		167
Sphaerocystis sp.											
Spyrogyra											
Staurastrum sp.				1							1
Tetrahedron minimum			83.3			83	106				91
Tetrastrum staurogeniaforma								1333.3			1333
Subtotal	90	30	6083.2	81	425	166	1068	1387.8	1256.1	66	1312
Cryptophytes											
Cryptomonas ssp.		55	41.7	38		167		166.7			38
Cryptomonas erosa				13		42		12.2	83.3		38
Cryptomonas marssonii		30	20.8	3	20.8						19
Cryptomonas rostratiforis		2									2
Katablephans ovalis		140	500	160		500		166.7	333.3		300
Rhodmonas minuta		20	666.7	1440	212.5	83	850	666.7	333.3		597
Subtotal		247	1229.2	1654	233.3	792	850	1012.3	1249.9		908
Blue-green algae											
Anacystis sp.											
Aphanocapsa sp.			16000		8925	83			8666.7		8419
Dactypococcopsis acicularis				60			1381	125	541.7		527
Oscillatoria sp.			104.2		24.5				36.7		55
Subtotal	50		16104.2	60	8949.5	83	1381	125	9245.1	91	5135

	7/1/86	11/11/92	4/14/93	6/29/93	8/3/93	12/5/93	4/21/94	6/28/94	9/20/94	85-86 Average	92-94 Average
Golden-brown algae											
Chromulina sp.				640							640
Chrysamoeba sp.					212.5			41.7	83.3		113
Chrysochromulina parva		280	2833.3	2680		1917	2444	1750	1000		1843
Dinobryon sp.			166.7		62.5		122	269.2	287.6		182
Kephyrion sp.			500	260	1912.5			212.5			721
Mallomonas sp.		10						41.7	41.7		31
Ochromonas sp.									166.7		167
Ophiocytium capitatum			83.3								83
Pseudopedinella erkensis		60	166.7	40			106	41.7			83
Synura adamsii		155									155
Subtotal		505	3750	3620	2187.5	1917	2672	2356.8	1579.3		2323
Other											
Phacus sp.											
Peridinium sp.			20.8								21
Ceratium hirundinella				2				0.8			1
Glenodinium sp.				8							8
Gymnodinium sp.											
Trachelomonas sp.									125		125
Chromulina sp.											
Microflagellates		20	250	240	3400	167	637	23587.5	333.3		3579
Other	70	20	270.8	250	3400	167	637	23588.3	458.3	40	3599
Total cell count	450	1384.5	32895.8	5675	15674.5	4830	7238	29032.6	14675	1071	13926
Station 4											
Chlorophyll-a (mg/l)		22.1	9.8	1.6	4	7.3	3.3	0	36.8	1.60	10.613
Secchi disk transparency (m)		3.9	3.0		4.4		3.8	3.4	3.3	3.49	3.613
Total phosphorus (mg/l)						0.015	0.0112	0.0088	0.0101	0.012	0.011
Dissolved phosphorus (mg/l)		0.00895	0.00487	0.00469	0.00242	0.0095	0.0082	0.0088	0.0079		0.007
Soluble reactive phosphorus (mg/l)		0.00114	0.00062	0	0.00127	0.0021	0.0002	0	0.0021		0.001

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